# Photovoltaic Cooking for the Developing World

# Final Design Report
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# Table of Contents

# List of Figures

# List of Tables

# Chapter 1 - Introduction

## 1.1 - Introduction

Many third world countries are using methods of cooking that are often dangerous to both themselves and the environment. The energy used for these methods include burning charcoal, cow manure, wood, and other materials which pollute the environment. We aim to present a new method of cooking that is reliable, cheap, safe, and renewable. Our solution is to use photovoltaic cells as the energy source to cook. The Photovoltaic cooker was designed to use minimal energy at a very low cost. Our main target is third world countries and will ideally be purchased for them through the use of carbon credits and from private organizations.

The cost of photovoltaic cells is decreasing rapidly. Currently, the cost of these cells is approximately $1.00 per Watt. Solar panels today are approximately 20% efficient, however this efficiency will continue to increase as the technology advances. In today's market there are cookers using photovoltaics, but they require upwards of 1000 Watts of power. Using that much power requires several solar panels and installation materials that are expensive and nonexistent in many third world countries. In order to make our design more realistic for third world applications, we are constraining our power output to 100 Watts. This will lower the cost of our solar panel to a reasonable expense. With such low power, it is unlikely that the cooker would ever reach temperatures high enough to cook because of the heat lost to the environment. By insulating the cooker, we hope to minimize that heat loss and yield high enough temperatures to cook.

Many third world countries use a boil and simmer method of cooking. This means we will only need the cooker to reach boiling temperature: 100°C. In a research article conducted by the Department of Physics at Sardar Patel University in India, it was reported that with the use of photovoltaic cells providing as little as 30 Watts of power, the experimenters were able to properly heat food. In two hours an internal oven temperature of 90°C was reached.

## 1.2 - Objective

Our overall objective was to design, build, and test an insulated "boil and simmer" cooker that is powered by a 100W solar panel for use in third world countries. In particular, we designed this for Uganda because they traditionally cook using a boil and simmer method. The system was designed with the Ugandan villagers in mind so that manufacturing, use, and maintenance could all be done on site in Uganda. A Quality Function Deployment matrix was designed to identify the stakeholders, customer

requirements, the engineering specifications needed to meet these requirements, and how our design compares to competitors. This can be seen in further detail by looking at the QFD shown in Appendix A.

There are several stakeholders that were kept in mind throughout the scope of our project. The African villagers are our primary customers since they will be using our product to cook food daily. For their convenience the product must be easy to use and manufactured with readily available tools and materials. Our design must be low cost so we can implement multiple cookers in villages with the use of Carbon credits. One of our biggest considerations was designing the cooker with the villagers' culture kept in mind. Ugandan culture traditionally cooks "boil and simmer" style foods so we designed our product around this.

The UN was another important customer to consider for our project since they determine the carbon credit funding for the cooker. They manage a system that distributes carbon credits for projects that are working to reduce emissions. The current method of Ugandan cooking generates a large quantity of carbon dioxide. Our product works to minimize the production of harmful emissions produced from cooking. A requirement was set to reduce the carbon footprint so that we can create a safer, less destructive method of cooking for Uganda as well as receive carbon credit funding.

Our final customers took into consideration were non-profit organizations such as Aid-Africa. They helped us with the implementation in Uganda and were a crucial part of the success of our project. The organization provided us with local knowledge and connections to the right villagers who received the first two solar cookers.

## 1.3 - Project Management

In this section we briefly discuss the timeline of this project and lists the major deliverables due. Individual team member's responsibilities are also discussed.

### 1.3.1 - Gantt chart

The following figures describe the timeline of the design phase of our project. Many of the dates and timelines are flexible. This means we may have started designing earlier than planned and constructed a prototype before the Build Phase started. More specific dates of the design phase are listed below in Figure 1.2

Table 1.1: Gantt chart dates

| | Task Name | Start Date | End Date | Duration |
|---|---|---|---|---|
| 1 | Project Proposal | 01/19/16 | 02/02/16 | 14 |
| 2 | Brainstorming/ Ideation | 02/02/16 | 02/09/16 | 7 |
| 3 | Idea Selection | 02/08/16 | 02/11/16 | 3 |
| 4 | Reflection #1 | 02/04/16 | 02/09/16 | 5 |
| 5 | Concept Modeling | 02/01/16 | 02/09/16 | 8 |
| 6 | Idea Refinement | 02/09/16 | 02/18/16 | 9 |
| 7 | Pugh Matricies | 02/09/16 | 02/16/16 | 7 |
| 8 | Final Decision Matrix | 02/16/16 | 02/25/16 | 9 |
| 9 | Schedule PDR with sponsor | 02/15/16 | 02/18/16 | 3 |
| 10 | Final Decision Matrix | 02/22/16 | 02/25/16 | 3 |
| 11 | Project Planning | 02/22/16 | 02/25/16 | 3 |
| 12 | PRELIMINARY DESIGN REPORT | 02/07/16 | 02/29/16 | 22 |
| 13 | Preliminary Design Review | 03/01/16 | 03/03/16 | 2 |
| 14 | Design Analysis | 03/07/16 | 03/10/16 | 3 |

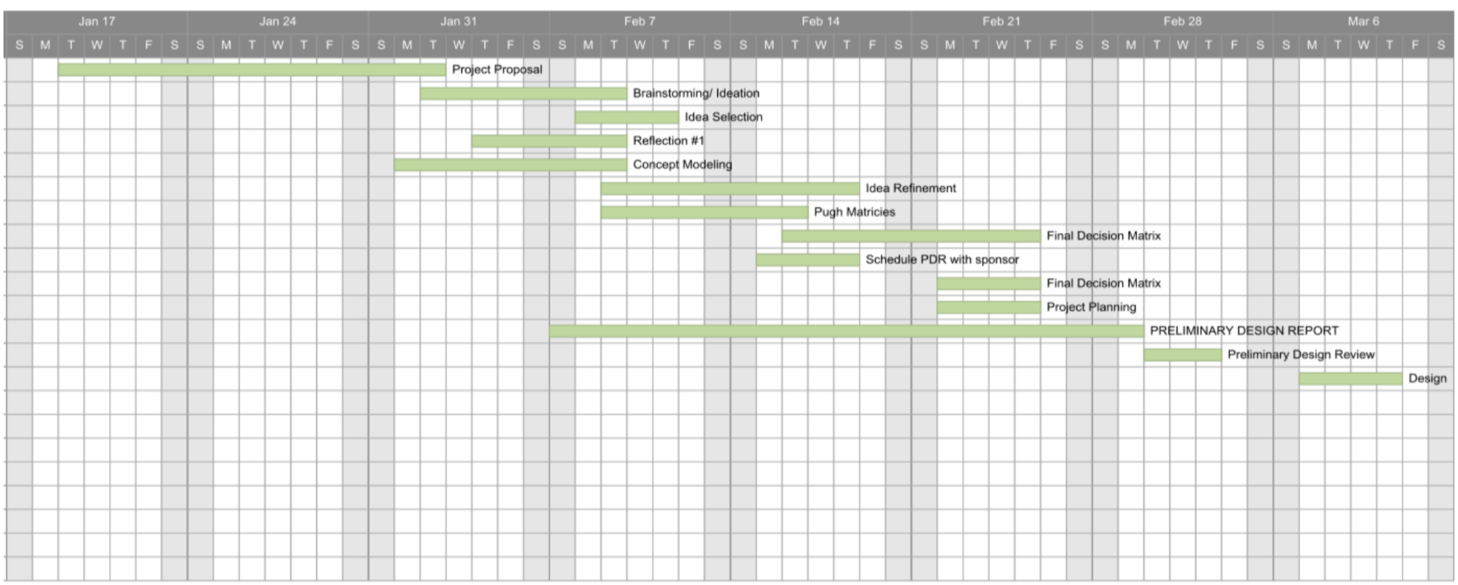



Figure 1.1: Design Phase Dates

| | Task Name | Start Date | End Date |
|---|---|---|---|
| 1 | CDR with sponsor | 04/29/16 | 04/29/16 |
| 2 | Final Design Report | 04/17/16 | 04/26/16 |
| 3 | 3rd Team Evaluations | 05/03/16 | 05/05/16 |
| 4 | Individual Ethics | 05/03/16 | 05/12/16 |
| 5 | Expo | 05/26/16 | 05/26/16 |
| 6 | 4th Team Evaluations | 06/01/16 | 06/02/16 |
| 7 | End of quarter status report | 05/26/16 | 06/02/16 |

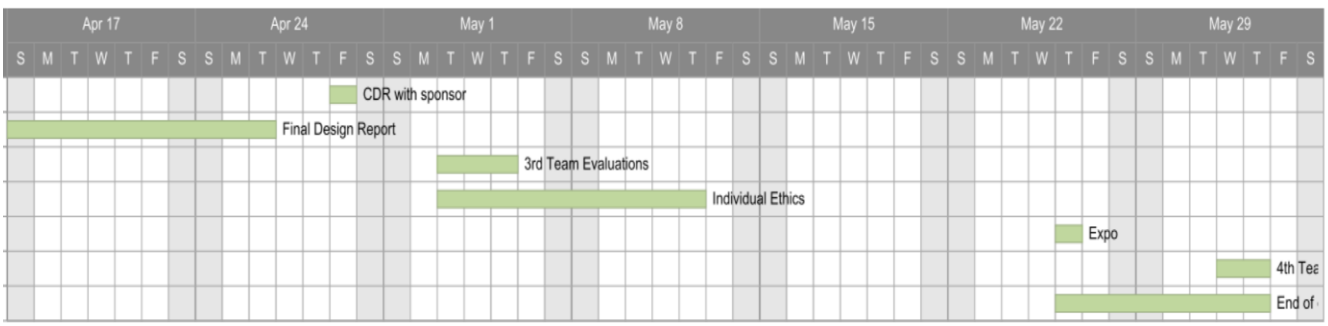
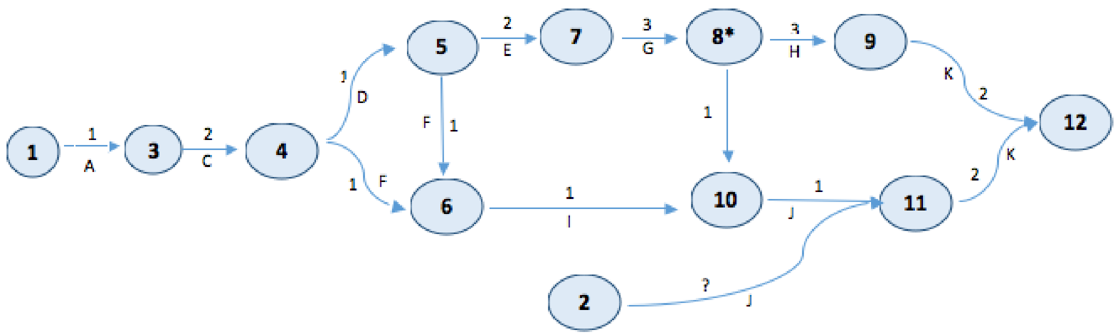



Figure 1.2: Specific dates during design phase

### 1.3.2 - PERT Chart

In order to further develop our project plan, we created a PERT chart that allows us to look at a critical path for completing the project. The PERT chart looks at which tasks can be completed at the same time so that we can work more efficiently during the course of the project. This can be seen in Figure 1.3 below.




| Index | Activity Description | Required Processor | Duration (weeks) |
|---|---|---|---|
| A | Ideation/idea refinement | N/A | 1 |
| B | Market Research | N/A | always |
| C | Design Analysis | A | 2 |
| D | Prototyping | C | 1 |
| E | Testing | D | 2 |
| F | Cost Estimate | C,D | 1 |
| G* | Field testing (Uganda)* | E | 3 |
| H | Iteration | G* or E | 3 |
| I | Production Analysis | G*/E,F | 1 |
| J | Project Expo Preparation | I,B | 1 |
| K | Final Report | J | 2 |

Figure 1.3: PERT chart

## 1.4 - Team Member Responsibilities

### 1.4.1 - Communication to sponsor

Omar was predominantly responsible for communication to our sponsor. However, this does not mean that other members of the group were unable to contact the sponsor. We met with our sponsor weekly as a group, as well as communicated via email from our shared team email address (photovoltaiccookers@gmail.com) if we had additional questions or topics of discussion for our sponsor in between meeting times.

### 1.4.2 - Secretary (documentation)

Chris was primarily in charge of documenting our project progress. In addition to Chris's documentation, members documented their progress on individual efforts. Each

week we will assess the progress of our weekly project goals and discuss this with our advisor. The leader of this meeting will rotate each week.

### 1.4.3 - Budget

Tyler managed the budget for this team. We aimed to make the product as inexpensive as possible while still attaining the designated specifications. Excluding Uganda implementation, there was

little to no travel costs associated with the design, building, and testing phases of this project so the budget will only include materials for manufacture and testing equipment.

### 1.4.4 - Manufacturing Considerations

Although all members should be included in the manufacturing consideration because all subsystems need to be fabricated and fit together, the majority of the manufacturing was done by the ME students. They also have more experience using manufacturing equipment and thus know what is possible to be made with the tools available to us. It is important that all members of the group agree on a design and acknowledge that their subsystem will work with the overall plan. This includes, but is not limited to dimensioning, subsystem integration, and calculations for expected testing values to ensure the manufactured product will be safe to use. Tyler and Chris led the insulation, and heat transfer subsystems of the project. Omar was in charge of the electronic components of our design. He made sure these could be incorporated effectively into the rest of the product.

### 1.4.5 - Research

All members were equally responsible for researching information for this project. We all collaborated at meetings to discuss what topics we researched and the conclusions that we have made from the research.

# Chapter 2 - Background

## 2.1 - Market Research

After conducting research, we found that the majority of the solar cookers on today's market use reflectors as a source of energy. When the reflectors concentrate the sun correctly, they can supply sufficient heat to thermal mass or even directly to the food. The downside of a reflection based solar cooker is that they are often large and difficult to set up. Additionally, they must be directed towards the sun correctly at all times or their efficiency will be greatly affected.

Another product that interested us is an insulated bag called The Wonderbag. These do not require solar energy to cook food, rather they utilize a traditional stove to bring food to the desired temperature then act as solely an insulator to keep this food warm. The Wonderbag is a stand-alone, non-electric insulated unit designed to reduce the amount of heating time required in the cooking of food. We aim to use the idea of reducing heat loss by means of thick insulation around an already hot pot of food. By integrating a heating element into the insulation, we will be able to bring the food to a boil, and keep it at a simmering temperature throughout the cooking process.

The latest technology in renewable energy stoves comes from a company called Biolite Energy. The Biolite camp stove generates usable electricity for charging mobile phones and other personal devices. Burning only wood, the camp stove creates a smokeless campfire that can cook meals and boil water in minutes. The technology works by capturing wasted heat from the fire through a heat probe. The heat is converted into usable electricity via a thermoelectric generator and sends electricity to a 5V USB port.

## 2.2 - Engineering Specifications

We created an engineering specifications table, seen in Table 2.1, to better understand our customers' requirements. Each specification has a target, tolerance, risk level, and compliance. The levels of risk are low (L), medium (M), and high (H). Compliance, or how each requirement will be verified, has four different methods: analysis (A), test (T), similarity to existing designs (S), and inspection (I).

Table 2.1: Engineering specifications table

| Spec # | Parameter | Requirements or Target | Tolerance | Risk | Compliance |
|---|---|---|---|---|---|
| 1 | Weight/Size | No requirement for max weight | N/A | N/A | N/A |
| 2 | Cost | $100 | ±$20 | M | A |
| 3 | Power | 100 Watts | Max | L | T |
| 4 | Safety | Withstand 100°C internal temperature, Outer temperature max of 56°C | Min/Max | H | A,T,I |
| 5 | Assembly | Assembled by no more than 2 people, using equipment readily available in Uganda | Max | M | T,S |
| 6 | Maintenance | Requires maintenance less than 3 times per year | Max | M | T,I,S |
| 7 | Operation | One person can operate completely | Max | M | I |
| 8 | Shipping | Prototype to be able to ship to Uganda | N/A | M | I |
| 9 | Material | Effective Insulation, cheap | N/A | H | A,T |
| 10 | Manufacturing | Manufacturing equipment available in Uganda | N/A | H | I,S |
| 11 | Heating | Boil 1L water in 90 mins, simmer temp throughout day | ±30 Minutes | L | A,T |
| 12 | Data Feedback | Log temperature readings during boil and simmer processes | N/A | M | T |
| 13 | Power Control | Split power to USB port when 100W is unnecessary for cooking | N/A | M | T,A |

These closely match the specifications set in the QFD [Appendix A]. The weight of our design is not an important specification since the cooker will be built into a home, thus it will not need to be moved. For this reason, there is no risk for the weight of our product. It will not be considered for any design decisions besides its shipping.

We set a target goal of $100 ±$20 to be able to set up several stoves in villages with the use of carbon credits. It is very important to keep the cost low. Due to the presence of non-profit organizations like Aid Africa and the UN's distribution of carbon

credits, funding can be found elsewhere. This $100 cost does not include the cost of a solar panel. The photovoltaic cells currently cost an additional $100; however, with the prices constantly decreasing this cost will be lower in the future.

In order to ensure that our product was safe we needed to design it to withstand temperatures of over 100°C without fully combusting or melting any of the components. We also wanted to ensure that people will not get burnt if they came into contact with any exposed surfaces on the cooker. According to the American Burn Association, it takes 15 seconds of exposure to open skin for an object at 56°C to severely burn you. We decided to set this to our maximum outer temperature to ensure the safety of the users. This is a high-risk specification because it could result in damaged houses or the injury of users. The outer surface temperature can be theoretically derived using our transient heat transfer model prior to testing. During testing and use, temperature will be regulated through thermocouple testing and visual inspection of the inner components after use.

We wanted the assembly, maintenance, and operation all to be relatively simple so that implementation in Uganda was feasible. A maximum of two people must be able to build a stove using only readily available tools in Africa. Low maintenance was another important characteristic. This is relatively easy to achieve considering the simplicity of design. The cooker should only require one person to operate. This means that the components such as the food and pot need to be easily removable from the cooker. These are all medium risk specifications. If not met, current Ugandan cooking methods will most likely be preferred over the solar cooker.

The material used for insulation must be low cost to ensure we stay within budget. The insulation material is fairly important because it determines the performance of our cooker under low power. Without good insulation, a 100W PV panel will not sufficiently heat water to a boil. This specification negatively correlates to cost due to the fact that manufactured insulation is typically expensive. Heat transfer analysis was used to distinguish what materials we can use and how much we will need.

We wanted to boil water in a reasonable amount of time so we used the target goal given in the PVE Cooker Patent that says a 100 W PV panel can boil 1 liter of water in 90 minutes. Once a boiling temperature is reached we required our design to maintain a simmering temperature for the remainder of the time food is cooking. This allows Ugandan users to cook multiple times a day in a similar fashion that they are used to. In order to verify this, heat transfer analysis and testing were performed.

# Chapter 3 - Design Development

## 3.1 - Brainstorming

Before we began to brainstorm different ideas for designs, we looked at Dr. Schwartz's Appropriate Technologies project. As seen in Appendix B.1, their simple design is just a bale of hay with a spot hollowed out to put the heater and pot into. This is a very basic design that does not satisfy our customer requirements and design criteria, but it gave us a foundation for brainstorming. It is discussed later in the report.

We began by looking at our engineering specifications and brainstormed different ways we could accomplish each task. All ideas were accepted no matter how outlandish in order to generate the highest quantity of designs. This brainstorming left us with many options to pursue as a first iteration. In order to determine which will yield the best results we put our designs and some intermediate elements through different decision matrices. The first matrix used in our decision process was the Pugh Matrix. We did this with different types of insulation, energy storage units, heating elements, and the loading techniques to establish our overall design.

### 3.1.1 - Insulation

As seen in Table 3.1, we used a Pugh matrix to help us decide which insulation would be best suited for our design. By looking at our specifications we decided that cost, thermal conductivity, R-value, availability, and resistance to moisture were the most important criteria when considering insulation types. We used fiberglass insulation as our datum because it is the most common type of insulation used as well as the insulation used in last year's project. After filling out the Pugh matrix, we found that cornhusks, mud, sand, and rock wool could be eliminated.

Table 3.1: Pugh matrix for insulation type

| Concept | Rice Hulls | PS | PU | Fiberglass | Corn Husk | Hay | Spray Foam | Mud | Sand | Rockwool |
|---|---|---|---|---|---|---|---|---|---|---|
| Criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Cost | + | - | - | D | + | + | - | + | + | - |
| Thermal Conductivity | S | + | + | | - | S | + | - | - | + |
| R Value | S | + | + | A | - | S | + | - | - | + |
| Availability | + | S | S | | + | + | - | + | + | - |
| Resistance to Moisture | + | + | + | T | S | - | + | - | - | - |
| Σ+ | 3 | 3 | 3 | | 2 | 2 | 3 | 2 | 2 | 2 |
| Σ- | 0 | 1 | 1 | U | 2 | 1 | 2 | 3 | 3 | 3 |
| ΣS | 2 | 1 | 1 | M | 1 | 2 | 0 | 0 | 0 | 0 |

Because our Pugh matrix was not weighted, we decided some of our results could be skewed. Although spray foam has a good thermal conductivity, R-value, and resistance to moisture it is very expensive per unit volume. We decided to research the cost of each insulation type and graph their price per unit volume vs. thermal conductivity. As a result of this graph, we found that spray foam and rock wool are significantly more expensive than any other type of insulation. For this reason, we decided not to include spray foam in our later analysis of insulation types despite its low thermal conductivity and resistance to moisture.

To further narrow down our insulation options, we weighted each of the criteria in a final decision matrix. Their level of importance determined each individual criteria weight. Cost was the most important factor to consider because size isn't a constraint of ours. If a much cheaper material has a worse thermal conductivity, we can simply add more insulation rather than spend unnecessary amounts of money on expensive insulation. Rice hulls and hay are much cheaper options than conventional insulation like polyurethane and fiberglass. All of these types of insulations have similar thermal conductivities, so the grading on that criteria is very similar. Durability is another important factor, but not as important as cost or thermal conductivity. The durability of polyurethane was much higher than all of the other insulations, because the other materials may be affected by water vapor released during cooking. None of the insulation types should pose a problem with our expected temperatures. The last factor we considered in our weighted decision matrix is availability in Africa. This will make it easier to manufacture and maintain because the materials will be readily available nearby. It would also decrease the cost of insulation to use a material that is readily available.

Table 3.2: Final decision matrix for insulation type

| Design Criteria / Design Concept | Cost | | Thermal Conductivity | | Availability | | Durability | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | 0.4 | | 0.3 | | 0.1 | | 0.2 | | |
| **Rice Hull** | 100 | 40 | 90 | 27 | 100 | 10 | 50 | 10 | 87 |
| **PU** | 50 | 20 | 100 | 30 | 50 | 5 | 100 | 20 | 75 |
| **Fiberglass** | 55 | 22 | 95 | 28.5 | 50 | 5 | 75 | 15 | 70.5 |
| **Hay** | 100 | 40 | 95 | 28.5 | 80 | 8 | 50 | 10 | 86.5 |

Concluding from our insulation final decision matrix, we are planning on using a readily available insulation in Uganda made from an organic material such as rice hulls or hay rather than a common insulation such as fiberglass or polyurethane foam. While the thermal resistance of the common insulation types was a little better, the cost of them was significantly more. Since the cost of our product is much more important than the size, we can use a slightly worse thermal conductivity that is much cheaper to achieve our desired level of insulation.

### 3.1.2 - Loading Technique

Another customer requirement that we brainstormed off of was how we were going to make the cooking pot easy to remove from our design. We did not want the user to have difficulty inserting or removing their food, resulting in spilling or burning themselves on the inside of the stove. We narrowed our ideas into another Pugh matrix to look at which matched the criteria the best.

Table 3.3: Pugh matrix for loading technique

| Criteria \ Concept | Top Load w/ Lid 1 | Top Load - Screw On 2 | Top load - Singe Cover 3 | "wonderbag" 4 | lever 5 | Front Load- Oven Style 6 | Drawer 7 | Pulley 8 | Insulated Pot Cover 9 |
|---|---|---|---|---|---|---|---|---|---|
| Ease of use | S | - | + | + | - | D | + | - | + |
| Safety | + | + | + | + | - | | + | - | + |
| Spilling | S | S | S | + | - | A | + | - | + |
| Manufacturability | S | - | + | + | - | | - | - | S |
| Durability | + | S | - | - | - | T | - | - | + |
| Heat Loss | - | + | - | - | - | | S | - | - |
| Cost | S | - | + | + | - | U | - | - | S |
| Size Versatillity | + | + | + | + | - | | S | - | + |
| Σ+ | 3 | 3 | 5 | 6 | 0 | M | 3 | 0 | 5 |
| Σ- | 1 | 3 | 2 | 2 | 8 | | 3 | 8 | 1 |
| ΣS | 3 | 2 | 1 | 0 | 0 | | 2 | 0 | 2 |

As seen from Table 3.3, the datum we used was an oven style front load, the design used for the previous insulated PV cooker. Many of our concepts could easily be eliminated from this Pugh matrix. The pulley and lever method did not meet any of the criteria better than our datum so both were eliminated. The techniques that best met our criteria were the top load with a cinch cover, the pot into a closable bag, and the insulated pot cover. These techniques were taken into consideration when we started ideating for our overall design.

### 3.1.3 - Electrical system

In order to test the characteristics of our solar cooker we will need several electrical components. An Arduino can be used as the microcontroller to communicate with all of the electronics. A thermocouple that is attached to the coil will send the temperature from the cooking element to the Arduino. An SD card attached to the Arduino will keep record of the time, temperature, and voltage of the solar panel. We will be able to use this data to test different insulators for the solar cooker. We are also going to attach a relay module to the Arduino in series from the solar panel to the heating element to shut off the heating element if it becomes too hot. Once a pot of water reaches a boiling temperature of 100°C, the relay will shut off power to the heating element. Figure 3.1 and 3.2 display the physical layout and connections of the electrical components.

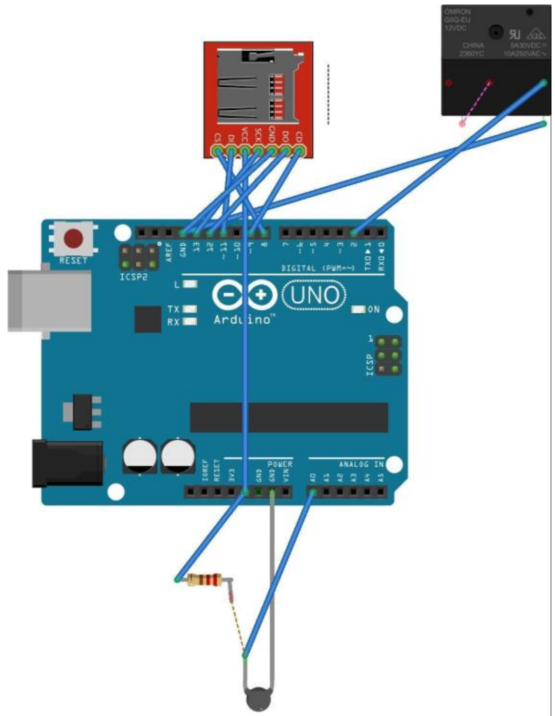



Figure 3.1: Breadboard diagram of testing equipment

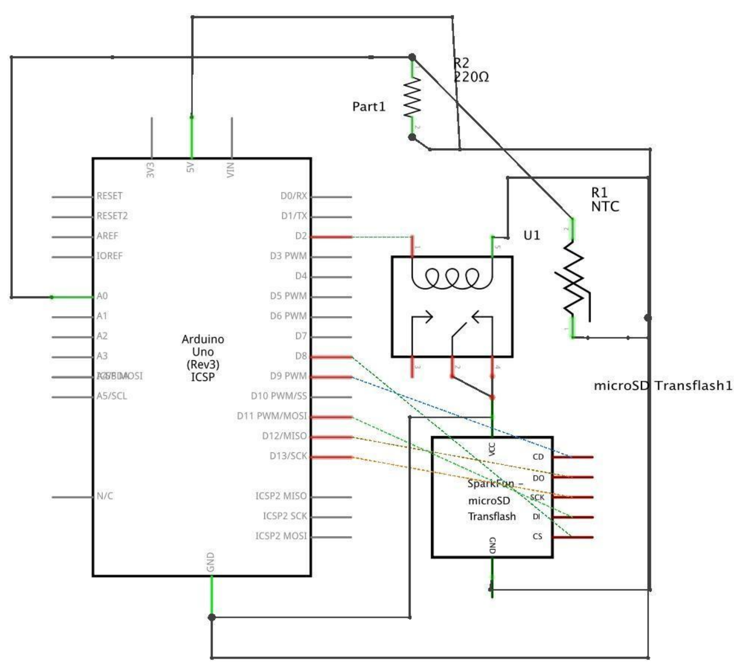



Figure 3.2: Schematic of testing components

### 3.1.4 - Energy storage

If our system is insulated well enough, we will have excess energy generated from the PV panel. We considered adding an electrical storage system to our solar cooker, but found that the additional cost of such system would put us over budget.

If feasible, the electrical storage system would be very easy to implement. We would simply divert the energy to a charging circuit similar to the one shown below in Figure 3.3, which is a charging circuit for lead-acid batteries. These are the most common batteries for energy storage as well as some of the cheapest. Further testing could be done to confirm which battery type would work best.

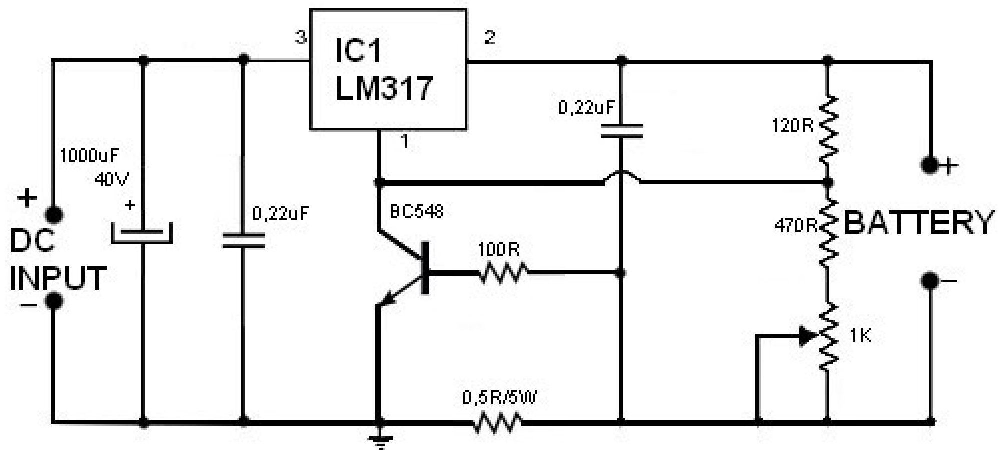



Figure 3.3: Charging circuit for lead-acid batteries

The charging circuit will be capable of charging two 12V 7Ah lead-acid batteries. The 1k potentiometer can be adjusted to set the desired current. We are able to calculate the charging current by performing the following calculation: Charging current = (1/10)*14Ah= 1.4mA. The input of three of the LM317 should be at least 15V to ensure the proper voltage is provided to the charging circuit. A heat sink will be beneficial for the LM317 since it will get hot.

### 3.1.5 - Overall designs

Our first design concept was a “hay-bale” cooker. This is the design that the applied technologies class built and tested. As shown in Appendix B.1, the cooker consisted of a hollowed out hay bale with a mud interior lining for sizing and structural support. The heating element and pot are placed in opening and covered with a lid. A second hay bale is placed over this for further insulation. Testing of this prototype resulted in a can of beans being fully cooked over a period of 4 hours. Unfortunately, a data logger was not used during testing so specific dataset is not available. Although we do not know the specifics of this testing, it was a good assessment of the capabilities of our other designs.

The second design concept was an adaption from the "Wonderbag" style that was introduced in the background section. This design is sketched in Appendix B.2. Our altered design integrates a heating element into the bag so that it will heat the food from room temperature and the maintain it at the desired cooking temperature. For this more insulation, a heating element, a thermal storage unit, and a way to replace the insulation would be required. The cloth interior will let water vapor from the food into the insulation. This could potentially ruin certain insulations (i.e. rice hulls and hay) and they would need to be replaced semi-frequently. There will be a zipper or other type of fastener in order to replace insulation. We could also coat the inside of the bag with a waterproof material and provide ventilation for the moisture released from the food during cooking.

Our third design, shown in the upper section of Appendix B.3, was a top loading, barrel shaped cooker. Theoretically, the interior of the barrel will be hollowed out so that a pot can fit snugly into. There are actually two designs here. One has a solid cylinder in the interior for a customized pot. The other has an interior cylinder that is made of a flexible material such as fabric so that any sized pot can be used. Insulation fills the space between the interior and exterior sections. This interior section will also contain a thermal storage block made with cement and a heating element. There were a few different designs for the top of the cooker including an insulated lid and a cinch cover.

Our fourth design, shown in the lower section of Appendix B.3, was a side loading, oven-style cooker. This design is very similar to a conventional household oven, except with a much smaller interior section designed to fit a single pot. This also allows for more room for insulation.

These four designs were put into a weighted decision matrix to help us decide on the design that best satisfies our specifications. The criteria for the matrix was decided by looking at the engineering specification we defined in Table 2.1. Most importantly we wanted our design to be low cost so that they are affordable for people in third world countries. We weighted this to be 25% of the overall decision. Heat loss, the ability to use any reasonably sized pot (size versatility), and safety were also of concern. In order to make food boil and stay simmering with such low power we need minimal heat loss so this was weighted as 17% of our decision. Safety was weighted as 15% of our decision. We did not want to have to manufacture a customized pot for our design, instead be able to use any pot the user may already own. We weighted this at 13% because, although important, we deemed it not as important as some of the other criteria. Ease of use, manufacturability, and durability were all considered when looking at our design choices as well.

Table 3.4: Final decision matrix

| Design Criteria | Ease of Use | | Safety | | Manufacturability | | Durability | | Size Versatility | | Heat Loss | | Cost | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Concept | 0.1 | | 0.15 | | 0.1 | | 0.1 | | 0.13 | | 0.17 | | 0.25 | | |
| Barrel, Lid | 90 | 9 | 80 | 12 | 90 | 9 | 90 | 9 | 80 | 10.4 | 80 | 13.6 | 80 | 20 | 83 |
| Barrel, Sinch Cover | 90 | 9 | 80 | 12 | 75 | 7.5 | 75 | 7.5 | 80 | 10.4 | 70 | 11.9 | 85 | 21.25 | 79.55 |
| "Oven" Style | 90 | 9 | 80 | 12 | 60 | 6 | 85 | 8.5 | 90 | 11.7 | 90 | 15.3 | 60 | 15 | 77.5 |
| Insulated Bag | 80 | 8 | 90 | 13.5 | 80 | 8 | 70 | 7 | 90 | 11.7 | 80 | 13.6 | 90 | 22.5 | 84.3 |

As you can see from Table 3.4, of our four overall design choices, the barrel with lid and the insulated bag designs scored the highest. Because both scored similarly and are for the most part simple designs, we have decided to go forth with both ideas. Both designs will be relatively easy to build and test. Our most important criterion is cost so, creating two functional prototypes is not beyond our project budget. A solid model of the Barrel with Lid design is shown in Appendix B.4

We looked at the engineering specifications table to ensure both designs would fit the characteristics well. First we analyzed the barrel and lid design. We were able to dismiss the weight and size of the barrel. Like any other design, the major cost is the solar panel. In this design we expected the other materials to run approximately $100 or less. Our power consumption of 100W would also remain the same. The insulated barrel will be able to withstand an internal temperature of 100°C and an outer temperature of 56°C. Assembly of the insulated cooker should take less than two days with only two people. The maintenance for this design would be minimal, mainly composed of replacing insulation when it gets rotten from rain or spilled food. One person would easily be able to operate the stove. The majority of the required materials for the insulated barrel with a lid are readily available in Uganda except for some of the electrical components which would require shipping to Uganda. The insulation for this design is dependent on what is most readily available in the region where it is implemented

The other design was inspired from a device called the Wonderbag, a device that has great thermal properties. This design is the most compact of the two since it is just an insulated bag. One of the benefits of this design is that it can be easily shipped and stored if desired. We plan on inserting the heating element inside the thermal bag. The electronics for this design would remain the same. The cost for this device would be relatively low as well since all the materials are easily attainable and cheap. Since these materials are readily available in Uganda, villagers could assemble stoves on-site. Similar to the previous design, there would be minimal safety considerations for this design. The only maintenance for this design would be for the electrical system and tearing of the outer bag. Operation for this design is relatively simple and could easily be done by a single person. Achieving boiling temperature in the desired time is dependent on the insulation and size, which can easily be adjusted.

## 3.2 - Preliminary Prototyping/Testing

In order to prove that we have a valid concept a rough prototype was built and tested. To simplify this, we used all store bought parts instead of fabricating any. Because

our design is so simple, it was easy to vary the geometry of different parts and still be able to model our final design accurately. A brief cost analysis of all parts bought for this prototype can be seen below in Table 3.5.

Table 3.5: Preliminary prototype cost analysis

| Part | Price | Quantity | Total |
|---|---|---|---|
| 100W Eco Worthy Solar Panel | $113.99 | 1 | $113.99 |
| Solar Panel Connections | $6.99 | 1 | $6.99 |
| Tarp | - | 1 | $0 |
| 16 gauge wire | $0.30/ft | 10 ft | $3.00 |
| 8" electric range burner | $7.50 | 1 | $7.50 |
| 10 qt galvanized pail | $9.88 | 1 | $9.88 |
| Outer plastic bin | - | 1 | $0 |
| Straw | - | | $0 |
| **Total** | | | **$141.36** |

We already had the majority of these parts so there was not much additional cost required to build our first prototype. Also, in our initial test we did not implement any thermal storage or temperature sensing. Additional parts needed for this were discussed in Section 3.1.4. A large plastic garbage bin was used as the outer container. This was filled halfway with straw, which is what the inner cook chamber rested on. A 10-quart steel pail bought from Home Depot was used for the inner cooking chamber. In order to fit the 8" electric range burner we had to drill two holes in the side of the pail so that the two burner terminals were protruding from the pail. This not only allowed the burner to fit snuggly inside of the cook chamber but also made wiring and unwiring the burner from the PV panel easy. Because our burner is rated for 2100W and 240V a resistance of 27.43 Ohms was calculated using Equation 1.

$$R = V^2/P \qquad (1)$$

$$R_{New} = \left(\frac{3}{R} + \frac{3}{R} + \frac{3}{R}\right)^{-1} = \frac{R}{9} \qquad (2)$$

This is much higher than our optimum resistance of 3.24 Ohms. Further analysis of optimum resistance can be seen in Section 4.10.1. In order to lower the resistance of the burner, we shorted it at the geometric thirds and rewired it to make it three separate resistors in parallel. As you can see in Equation 2 this decreases the resistance by a factor of 9 giving us a resistance of 3.04 Ohms. The modified burner can be seen in Figure 3.4.

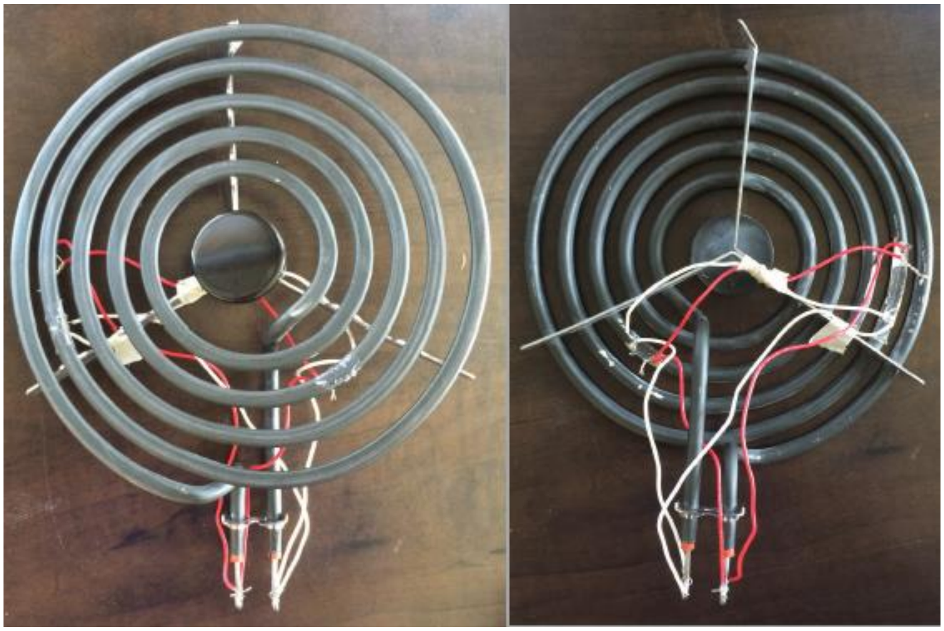


Figure 3.4: Modified burner

Once the burner was modified to increase the power output, we wired it to the PV panel using 16-gauge wire. Straw was then stuffed around the inner cook chamber to insulate the sides. This can be seen in Figure 3.5.

Figure 3.5: Top view of prototype

For our initial test, we wanted to get an idea of around how long it would take to boil 1 liter of water on a sunny day. A K type thermocouple was attached to the pot to measure the temperature of the water near the bottom of the pot. A tarp was then filled with straw and placed over the pot to fill the rest of the bin with insulation. Temperature measurements were taken every 5 minutes for 90 minutes. The corresponding graph can be seen below in Figure 3.6. The slope of this figure should realistically be decaying over time, however at these relatively low temperatures, our temperature vs. time curve is still in a linear region.

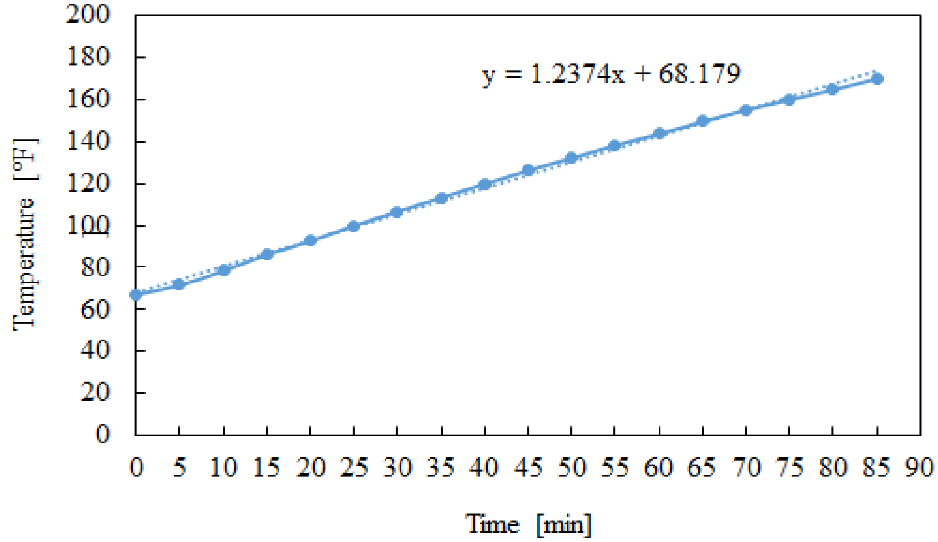



Figure 3.6: Preliminary testing temperature vs. time

Due to time and sunlight constraints, this test could not be completed and the water was not brought to a boil. As you can see from the graph, the temperature increased in a seemingly linear manner from its initial temperature of 67.2 °F to 171.6 °F. Using the linear fit equation, we calculated a time to boil of about 115 minutes from an initial temperature of 70°F. This is about 1.5 times longer than our initial analysis predicted. There are several explanations to this difference. Our analysis is for a steady state system with no convection so it is not an accurate model of what is happening inside of the oven. Also, the thermal conductivity of the straw used in our analysis was 0.06 W/m*K, a value found through an experiment conducted by Shaw. This could be an inaccurate value for the insulation we used based on the actual material and how densely it was packed.

One thing that was observed when taking the pot out after being heated is that the steel pail used for the inner cooking chamber was very hot. Lots of energy was being conducted to the pail because it is in direct contact with the burner. In order to solve this issue for our second prototype we have decided to pick a material with a lower thermal conductivity as well as mounting the burner differently inside of the cooking chamber. This will greatly decrease the amount of energy going into heating the inner cooking chamber and focus the energy on the pot containing food.

# Chapter 4 - Description of the Final Design

## 4.1 - Overall Description

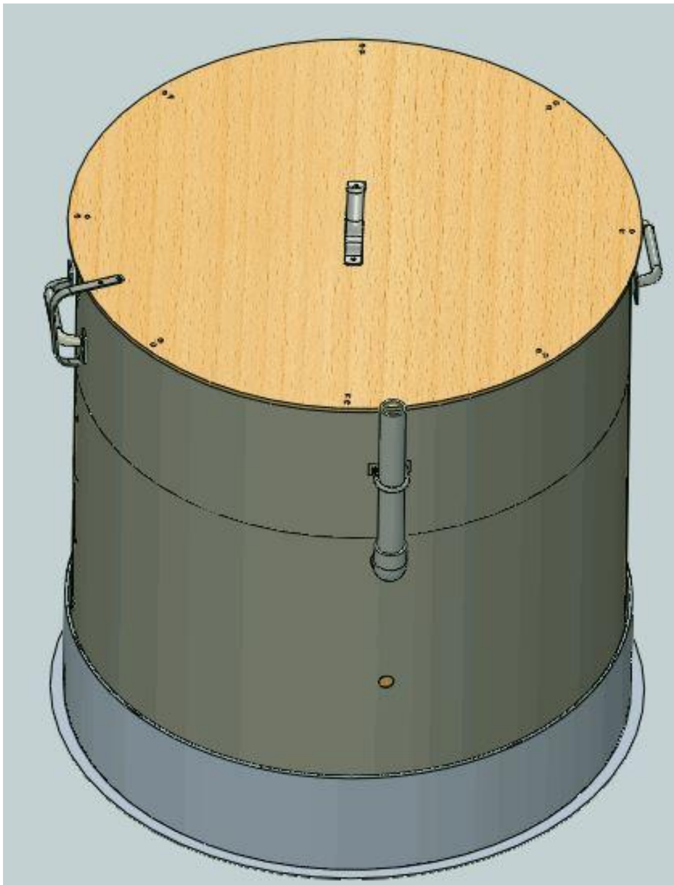


Figure 4.1: Overall design

Our overall design can be seen in Figure 4.1. Our design is very similar to the prototype we built, but is larger and has more features to make the design user-friendly and robust. The design consists of five main parts, which are generally described in this section and further laid out in the Detailed Design section. The five main parts of our design include:

1. Base
2. Outer cylinder
3. Inner cook chamber
4. Lid
5. Electrical system

The oven is designed so that one person can cook food throughout the day. The user will add food in a pot to the inner cooking chamber at the beginning of the day, then slowly simmer the food until it is cooked. Our oven will not cook food quickly, but will allow the user to cook food with a minimal amount of attention after the food has begun cooking. With its simple, yet robust design, there will be little maintenance required for use. We hoped that its ease-of-use and durability will help influence Ugandan locals to fully implement it into their daily lives, solving the problem of inefficient cooking in Uganda.

## 4.2 - Base

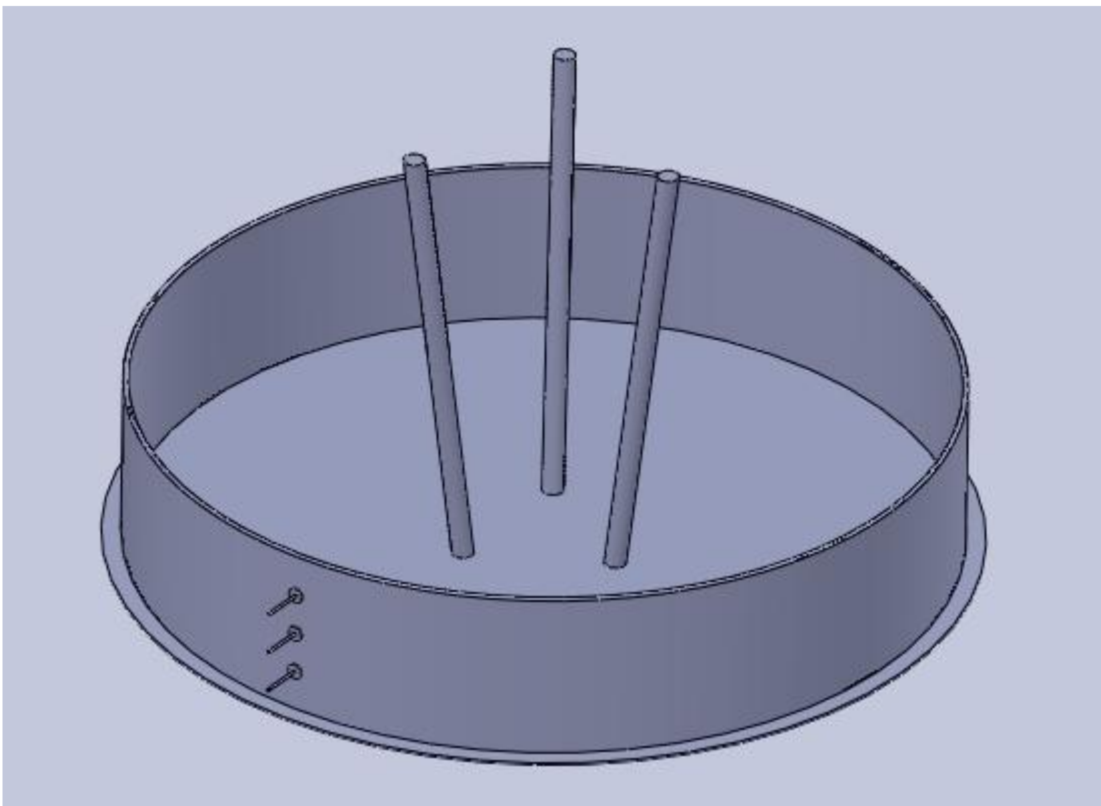


Figure 4.2: Base rendering

### 4.2.1 - Function

The base of our design was meant to stay in the user's home permanently. It adds structural support to the outer cylinder and has a stand for the inner cook chamber so that it doesn’t have to rest on insulation. This will decrease the risk of the inner chamber falling over. The base plate also protects the insulation from any rain runoff that may occur during the wet season in Uganda. A rubber tube will be wrapped around the bottom edge for safety purposes.

### 4.2.2 - Components (material selection, tolerancing, etc.)

Base plate:

The main purpose of the base plate is to keep the inner insulation from being destroyed. It also gives the entire oven support because its diameter is wider than that of the oven. To minimize rusting, we chose 22-gauge galvanized steel sheet metal. Ideally this part would be thicker to give it more structure and weight. The only tolerance put on this part is a minimum diameter equal to the diameter of the outer cylinder. Having a larger diameter will only add more support. A detailed drawing of this part can be seen in Appendix C.1.

Cooking chamber supports:

Since these will be protected from the rain we do not have to spend extra money on galvanized or stainless steel. Rebar is very cheap and easy to work with so we chose to use ½" steel rebar. This will lower costs, make it easy to manufacture, and ensure that we will be able to get all of our materials in Uganda. The way these parts are designed makes them still functional if they differ in lengths and angle welded. The cooking chamber will still be able to be placed on the supports if they are different lengths. A detailed drawing of this part can be seen in Appendix C.1.1.

Outer cylinder supports:

This part must be able to be rolled and cut fairly easily so we selected 22-gauge galvanized steel sheet metal. This will protect it from rust as well. Holes must be located on the part so that once it is rolled into a cylinder it can be riveted easily. The length and height can vary by a few inches as long as its radius is larger than that of the outer cylinder. A detailed drawing of this part can be seen in Appendix C.1.2 and Appendix C.1.2

### 4.2.3 - Manufacturing

- Cut a 30-inch diameter circle from a sheet of 22-gauge galvanized steel
- Weld 3, 16-inch long pieces of rebar to this base plate
    - The base of these pieces of rebar should be 2.5 inches from the center of the base while the top of the rebar should be 4.5 inches from the center (radially). At this angle the interior-cooking chamber will rest on the rebar.
- Using a shear, oxy acetylene torch, or a press punch (whichever is readily available) cut a sheet of 22 gauge galvanized steel that is 96 inches by 6 inches
    - Punch 3 holes along the short edges of this sheet
        - The center of these holes will be 1.5 inches apart, and 1.5 inches from the edge of the sheet
    - Roll the sheet into a 28.66-inch diameter cylinder using a sheet metal roller, the holes should line up at this dimension
    - Rivet the hole to hold the cylinder in place
- Weld the cylinder to the base plate

- The outer cylinder below will fit into this base and be supported by it

*Drawings with dimensions can be found in Appendix C.1

## 4.3 - Outer Cylinder

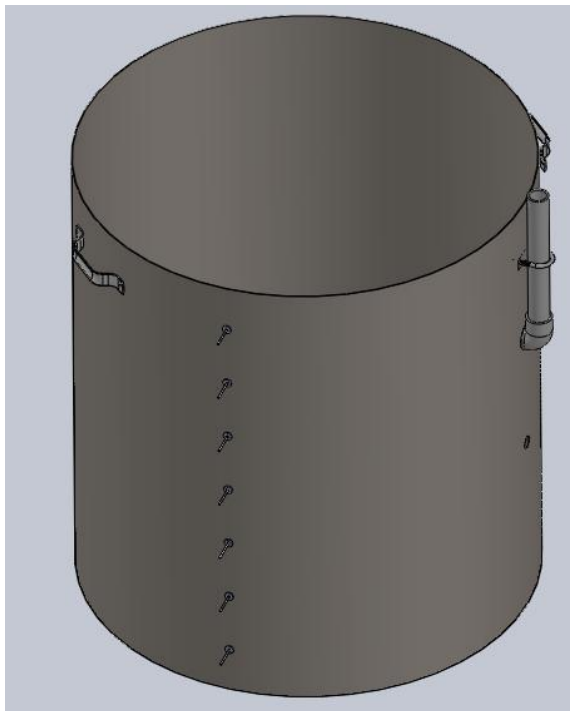


Figure 4.3: Outer cylinder rendering

### 4.3.1 - Function

The outer cylinder is what contains the insulation around the inner cooking chamber. It is lifted over the base and slid into the wider cylinder that is attached to the base. This will keep it from tipping over or sliding around when in use. We designed the outer cylinder to be light enough to be lifted using the handles so that the user can bring it outside or anywhere else in the house that they may want to temporarily use it. Without the base it will still stand, but will not be as sturdy so we do not intend users to permanently use the oven without the base. As you can see from Figure 4.3 we added a vent attached to the outer cylinder that connects to the inner cook chamber so that moisture does not build up in the cooking chamber. Trapping moisture in the cooking chamber would cause the insulation directly above the chamber to rot quickly. The addition of a vent was necessary even though heat will be lost through it. The hole directly below the vent is for the wiring from the PV to the burner. This keeps the wire out of the way when opening and closing the lid of the oven. To prevent wire fray and cutting, a rubber grommet will be added to the hole. Also, to decrease the risk of injury, rubber tubing will be cut and wrapped around the top edge of the outer cylinder. This will

take the risk of someone cutting their hand on top of the oven as well as protect users from the pinch point between the lid and outer cylinder when closing the oven.

### 4.3.2 - Components

Cylinder:

The cylinder is the main component of this part of our design. It will be made of the same material, 22-gauge galvanized steel sheet metal, as the base support for the cylinder. This will allow us to roll then rivet the sheet metal easily in the same way that the base support was rolled. We were worried about the steel being too heavy for someone to lift so we chose the gauge of sheet metal based off of what its total weight would be after it is cut. With 22-gauge sheet metal this part would weigh around 26 lbs. not including the handles and vent. This is light enough for the user to be able to move this part of the oven fairly easily. We chose galvanized steel to prevent rusting as well. A detailed drawing of this component can be seen in Appendix C.2.1 and Appendix C.2.2.

Handles:

The handles are an important part of the outer cylinder because it allows the user to pick up the oven more easily in order to move it or replace the insulation. To decrease cost and ensure that we will be able to get the materials in Uganda we are going to use ½” rebar that will be bent and welded onto the sides. This is the same material used for the inner cooking chamber base supports so this minimizes the number of materials we would have to order.

Vent:

The vent will be inserted into the inner cooking chamber so it will need to withstand higher heat than conventional PVC pipe can withstand. We chose 1” CPVC pipe so that it can withstand higher temperatures without melting. CPVC is also more corrosion resistant than conventional PVC. This is important because it will be in contact with water vapor while in use.

The U-bolt is a part that will be bought off of McMaster Carr to decrease the amount of custom fabrication required. It is a 1-⅜” zinc-plated U-bolt. The zinc plating will reduce corrosion. It is sized so that it can accommodate 1” CPVC pipe easily without being perfectly aligned.

### 4.3.3 – Manufacturing

- The shell of this cylinder will be made from a 22-gauge galvanized steel sheet
    - Take a sheet of 22-gauge galvanized steel that is 96 inches by 30 inches
    - Punch 7 holes along the short edges of this sheet
        - The holes will be 4 inches apart, and 4 inches from the edge of the sheet
        - The end holes should be 3 inches from the top and bottom edge
    - Punch a 1.5-inch diameter hole in the center of the sheet, 9 inches from the top edge

- Punch a 0.5-inch diameter hole in the center of the sheet, 12 inches from the bottom edge
  - This hole will be for the wires from the PV panel to the burner
- Punch 2 0.25-inch holes 4 inches from the top edge of the sheet. These holes should be 1 inch apart, centered at the middle of the sheet.
  - The distance between these holes is more important than the position
  - These holes will be used to fasten the U-bolt to the shell
- Wrap this sheet into a 27-inch diameter cylinder. The edge holes should align
- Rivet the holes to hold this sheet metal in the cylinder shape
- Insert the CPVC piping and CPVC elbow through the ventilation hole
- Fasten the U-bolt around the CPVC to hold it in place
- Bend 2, 8-inch-long piece of ½ inch rebar on both ends, 1.5 inches from the ends
  - Weld this rebar to the sides of the steel shell, 4 inches from the top

*Drawings with dimensions can be found in Appendix C.2

## 4.4 - Inner Cooking Chamber

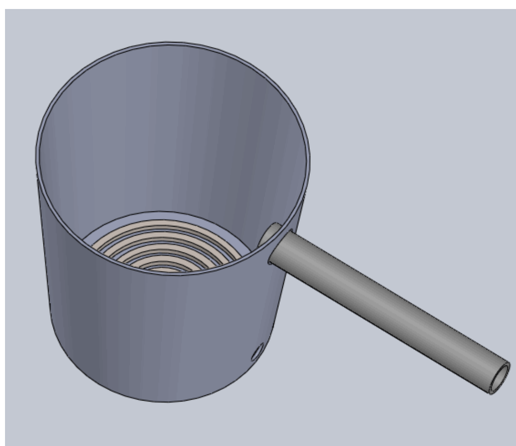


Figure 4.4: Inner cooking chamber rendering

### 4.4.1 – Function

Figure 4.4 shows the inner cooking chamber with the burner inside of it and ventilation protruding. The pot of food will be placed inside this during heating. The cook chamber will be a handmade part out of a material with low thermal conductivity such as clay, ceramic, or mud bricks. This will reduce the heat lost to the inner chamber walls. We designed the supports on the base so that the inner cooking chamber can have very broad tolerances and still be supported well. The main constraint that must be met is the bottom diameter must fit the burner. The holes at the bottom of the chamber are for the

wiring to the burner. Because it will not be made of metal like the outer cylinder, rubber grommets are not required for these holes.

### 4.4.2 – Components

Burner:

There are several different options that we have for burners. Conventional electric range burners have too high of a resistance which would greatly decrease our power (further analysis in Section 4.8.1). To lower resistance we can modify the burner so that it is three resistors in parallel, which would decrease resistance by a factor of 9.

Cook Chamber:

The cooking chamber will be either a bought or handmade part. It will be made of a ceramic, clay, or mud material depending on what's most readily available. These materials have a lower thermal conductivity than metals so that less heat is dissipated to the insulation directly below the burner. This will also focus more of the burner's energy on the pot and food. The chamber must be able to accommodate the burner and vent. To do this the bottom diameter must be large enough and three holes must be drilled in it.

### 4.4.3 - Manufacturing

The manufacture of this part really depends on what is available in Uganda. Ideally, the part would be made from a hard material with a low thermal conductivity as stated above. The ideal choice would be to buy clay or ceramic pots of a similar size if that is possible. If not, the next option would be to make a pot from ceramics, clay, or mud bricks. If neither of those options are possible in Uganda or our manufacturing facility, there then a tin bucket would need to be purchased to use for the structure of this part and an insulating plate will be placed inside under the burner to help direct heat upwards into the pot and food rather than down into the cooking chamber and structural supports.

Once a "cooking chamber" has been decided on from the available resources in Uganda, a 1.5-inch hole will be made near the top for the CPVC ventilation. A 0.75-inch hole will be made 0.5 inches from the bottom for the wires to run through. The burner will be placed in the bottom of this chamber. If this part ends up being made from a highly thermal conductive material a ceramic plate the same size, as the bottom will be under the burner.

*Drawings with dimensions can be found in Appendix C.3.
**The dimensions for this part are arbitrary because the pot used for manufacturing in Uganda may differ from the one we designed.

## 4.5 - Lid

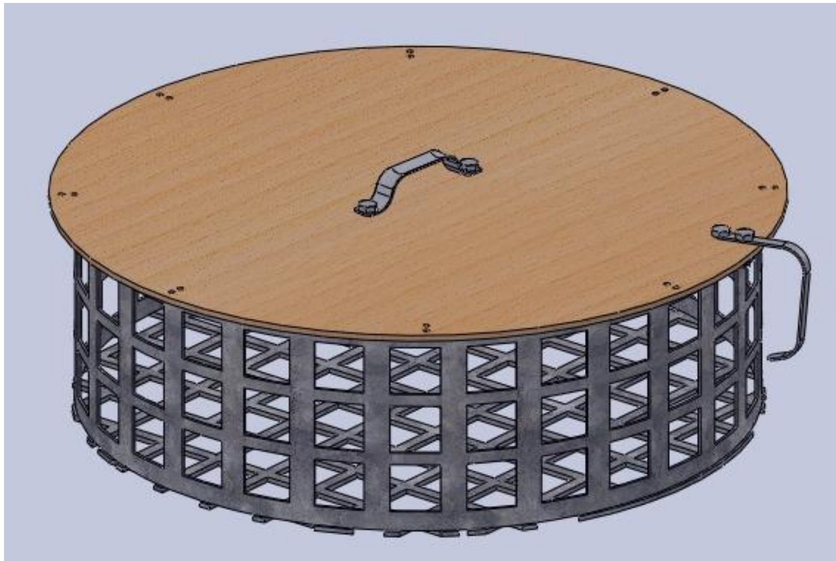


Figure 4.5: Lid rendering

### 4.5.1 – Function

The lid sits on top of the outer cylinder while the oven is in use, protecting the inner cooking chamber and insulation. Underneath the lid, more insulation is attached so that when you close it the top of the cooking chamber is insulated. This makes it so the user does not have to pack insulation over the pot every time they insert or remove a pot. The casing for the insulation is made of ¼” chicken wire so that insulation doesn’t fall into the cooking chamber, creating a fire hazard. A handle was added on top of the lid to make closing and opening the oven easy. So the lid isn’t put on the ground when taken off, a hook was attached so that the lid can be hooked onto the one of the handles on the side of the outer cylinder. This will increase the life of the lid and insulation underneath it.

### 4.5.2 – Components

Top:

The top of the lid will be made of 15/32” treated plywood. This material is cheap and sturdy enough to withstand the loads that will be put on the lid. It is important for the lid to be water and corrosion resistant due to the wet season in Uganda so treated plywood was our best option with greatly increasing price and weight. The top is just a circle that must have a minimum diameter of half an inch more than the outer cylinder’s diameter. In order to attach the chicken wire insulation holder underneath it, 8 series of two holes must be drilled around the perimeter of the top. This will allow the manufacturer to simply zip tie the chicken wire underneath the top. Holes must also be drilled in the top for the hook and handle. A detailed design of this component can be seen in Appendix C.4.1

Handle:

The handle is a purchased part off of McMaster Carr. It is a stamped stainless steel part, which will be strong enough to withstand the load of lifting the lid as well as not rust in the rain. A detailed drawing of the handle can be seen in Appendix C.4.2. The handle will be fastened using 2 stainless steel hex nuts and bolts with stainless steel washers on the underside of the lid to disperse load. The bolts are M10 bolts that are 30mm long. These are the same bolts that will be used on the hook, which is discussed next. Detailed drawings of the nuts, bolts, and washers can be seen in Appendix C.4.4 - C.4.6

Hook:

The hook selected will also be purchased off of McMaster Carr. It is a zinc plated steel hook with a 5" projection. This will prevent corrosion and give us enough hook space to easily be able to attach the lid to the handle of the outer cylinder. A detailed drawing of the hook can be seen in Appendix C.4.3. The hook will be attached using the same nuts, bolts, and washers as the handle.

Insulation holder:

¼" mesh chicken wire will be used for the insulation holder. This material is very easy to manipulate so it can be hand rolled into the cylindrical shape we have designed. It can also be cut very easily which helps with ease of manufacturing. The mesh chosen is small enough to hold the insulation without it dropping into the cooking chamber.

Zip ties:

In order to keep costs down, the mesh will be zip-tied to the lid. These will not be under much load so the zip-ties should not fail.

### 4.5.3 - Manufacturing

Manufacturing the lid of our solar cooker.

- Cut out a 29-inch diameter circle from a sheet of 15/32 inch treated plywood
    - Drill 8 sets of 2 0.25 inch holes around the perimeter of the circle
        - Each individual set of holes should be 0.5 inches apart
        - The sets are positioned 45 degrees in relation to each other
        - These will be used to fasten the insulation support to the lid
    - Across the diameter of the circle, drill 2, 0.25-inch holes, 5.75 inches apart
        - The center of the circle should between these two holes
        - These will be used to fasten the handle to the lid
        - The distance between the holes is more important that the position.
    - Fasten the handle to the lid using 2 M10 bolts, nuts, and washers
    - Drill 2 more holes along the edge of the circle
        - These holes will be 1 inch apart with the outside hole 0.75 inches from the perimeter.
        - The distance between the holes is more important that the position.
    - Fasten the lid hook to the lid using 2 M10 bolts, nuts, and washers

- Cut a 90 inch by 8.5-inch rectangle out of 0.25-inch chicken wire
  - Wrap the chicken wire into a 27-inch diameter by 8.5-inch height cylinder
    - Use zip ties to fasten the chicken wire to itself in this shape
- Cut a 27-inch diameter circle out of 0.25-inch chicken wire
  - Fasten this circle to one end of the cylinder using zip ties
- Fill this cylinder with insulation
- Fasten the cylinder to the lid with 8 zip ties through the perimeter holes

*Drawings with dimensions can be found in Appendix C.4

## 4.6 - Electrical System

In order to ensure that the coil does not overheat, we designed an electrical system to turn off the coil when it reaches a set temperature. The system consists of an Arduino that is connected to a thermocouple and also connected to a relay. The schematic in Figure 4.6 is shown below. The thermocouple will be installed by wrapping it around the heating element to ensure a proper temperature is read. This toggle temperature will be 100 degrees Fahrenheit cooler than the combustion temperature of the insulation The relay will be connected in series on the positive lead of the solar panel output.

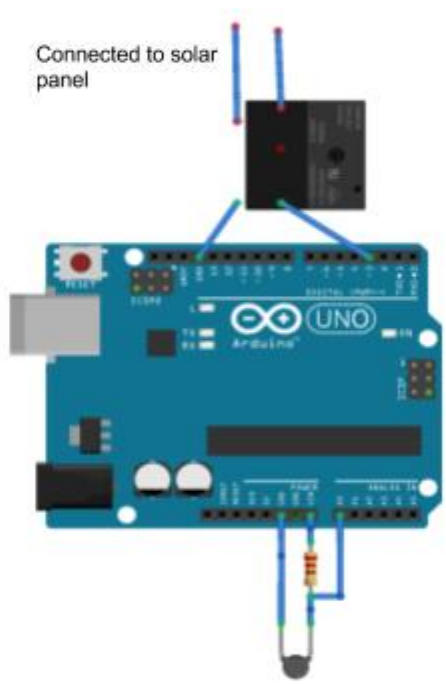



Figure 4.6: Electrical system

Another safety mechanism that we could implement instead of the selected electronics is a bimetal temperature switch which will automatically open the circuit at a defined temperature.

## 4.7 - Cost Analysis

Table 4.1 below shows the itemized list of material costs. Some parts will be manufactured in-house, while others will be bought. The parts that will be manufactured are the base plate, outer and inner supports, outer container, inner cooking container, top lid, and the lid insulation container. All other parts, fasteners, and electronic equipment will be purchased. As you can see from the table the final material cost of our design is $116.79. This does not include the cost of manufacturing, labor, and overhead. If we were to manufacture our design on a larger scale we could buy materials in bulk and decrease our total materials cost so price would most likely even out to around $100, which was the specification we set initially.

Table 4.1: Cost analysis

| **Part** | **Material** | **Price** | **Quantity** | **Total** |
|---|---|---|---|---|
| - | - | ***[$/unit length]*** | ***[ft.],[ft^2] ,piece*** | ***[$]*** |
| **Parts** | | | | |
| Base Plate | 22 ga. galvanized steel sheet metal | $1.94 | 3.8 | $7.35 |
| Outer Cylinder Support | 22 ga. galvanized steel sheet metal | $1.94 | 4.59 | $8.88 |
| Inner Cylinder Support | 1/2" rebar | $0.22 | 4 | $0.89 |
| Outer Container | 22 ga. galvanized steel sheet metal | $1.94 | 18.75 | $36.28 |
| Inner Cook Chamber | Ceramic/clay/mud | | 1 | $0.00 |
| Lid Top | 15/32" treated plywood | $0.84 | 7.6 | $6.36 |
| Insulation Holder on lid | 1/4" chicken wire | $0.90 | 10.5 | $9.42 |
| Outer Container Handle | 1/2" rebar | $0.22 | 1.33 | $0.30 |
| Lid Handle | Stamped stainless steel | $6.00 | 1 | $6.00 |
| Hook | Zinc plated steel hook | $4.80 | 1 | $4.80 |
| Vent | 1" CPVC | $1.91 | 1.67 | $3.19 |
| Vent Elbow | 1" CPVC elbow | $2.47 | 1 | $2.47 |
| Rubber Tubing | 1/2" rubber pipe insulation | $0.63 | 15.2 | $9.50 |
| Rubber Grommet | 3/4" rubber grommet | $0.14 | 1 | $0.14 |
| **Fasteners** | | | | |
| Rivets | 1/4" stainless steel rivets | $0.50 | 10 | $4.96 |
| U-bolt | 1-3/8" zinc plated | $1.30 | 1 | $1.30 |
| Zip ties | 8" plastic zip ties | $0.02 | 16 | $0.32 |
| Bolts | M10 30mm stainless steel hex bolts | $0.73 | 4 | $2.93 |
| Nuts | M10 stainless steel hex nuts | $0.39 | 4 | $1.57 |
| Washers | M10 stainless steel flat washer | $0.12 | 4 | $0.49 |
| **Electronics** | | | | |
| Adjustable knob temperature control | | $9.65 | 1 | $9.65 |
| Ibutton | Borrowing data logger | N/A | 5 | N/A |
| Burner | 6" electric range burner | $10 | 1 | $10.00 |
| 16 gauge wire | 16 ga. insulated wire | $0.30 | 10 | $3.00 |
| PV Connectors | Plastic | $1.43 | 1 | $1.43 |
| **Total** | | | | $116.79 |

## 4.8 - Assembly

Some assembly will be required once it is manufactured. If there is no insulation at hand in the manufacturing facility, then the user must use their choice of insulation for the lid and zip tie it shut. This process is the same for the user as it would be for the manufacturer, so this process can be seen again in Section 4.5.3. Other than that all assembly instructions are below:

1. Place base where you will cook the majority of the time
2. Lift outer cylinder over base and slide it inside of the cylinder welded to the base
3. Densely pack the outer cylinder with straw (or any other form of insulation at hand) until it is up to the wire hole
4. Place inner cooking chamber on the stand inside the cylinder
5. Put PVC pipe vent into inner cooking chamber hole and attach the other end to the elbow
6. Thread wires through the wiring hole and connect them to the connectors on the electronics box.
7. Fill the rest of the space with insulation until it is level with the top of the inner cooking chamber
8. Place lid on top

## 4.9 - Maintenance

The main worry regarding maintenance is the failure of the electrical system. In order to decrease the likeliness of failure we designed the electrical system to be as simple as possible. If, after testing, we conclude that an Arduino data logger is not necessary we can always use a bimetal switch that is only one small part. This will be less likely to be tampered with too.

Maintenance may need to be done on the insulation in order to keep it from rotting. Further testing must be done to figure out how often this maintenance will occur, but it will most likely need to be changed during the wet season. We designed the oven to protect the insulation as well as possible and also to make changing out the insulation easy. The user will have to cut the zip ties on the bottom part of the chicken wire underneath the lid to get the insulation out. Once removed, they can pack new insulation and zip-tie it together.

## 4.10 - Engineering Analysis

### 4.10.1 - Optimum Resistance

We measured the resistance of the burner and found that it was 27.4 ohms. This would consume 740.74mA. At this current, the burner would take a couple hours to bring water to a boil. In order to maximize the power output from our heating element, we

calculated an optimum resistance using two methods. The first involved using the "Electrical Characteristics" graph given by Eco-Worthy, the manufacturer of the solar panel. As seen in Figure 4.7, the power curve given by the manufacturer can be analyzed graphically in order to calculate an optimum resistance.

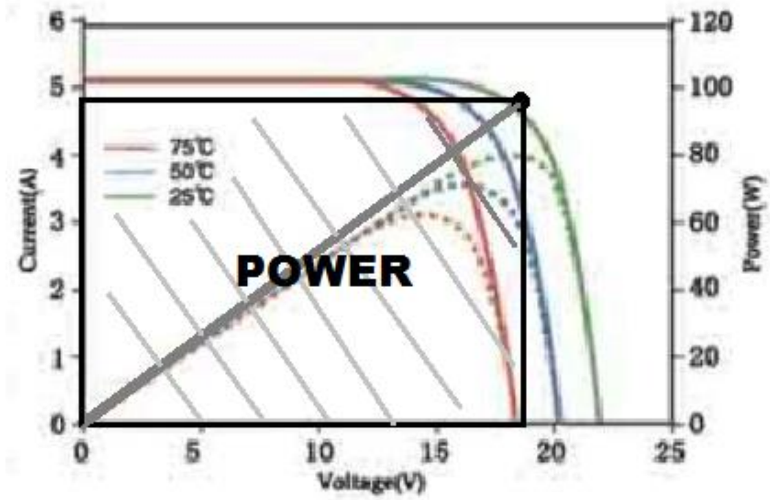



Figure 4.7: Power curve of PV panel

The power is maximized at the point chosen in the Figure 4.7. The current and voltage was obtained from a point on the graph and the optimum resistance of 3.05 Ohms was calculated by equation (4.1).

$$R = \frac{V}{I} = \frac{18\,V}{5.9\,A} = 3.05\Omega \qquad (4.1)$$

Another method was used to calculate an optimum resistance. As seen in Figure 4.8, by modeling the PV panel as a voltage source with a resistance and our burner as a single resistor attached in series to the PV panel you can easily calculate when the load resistance optimizes power.

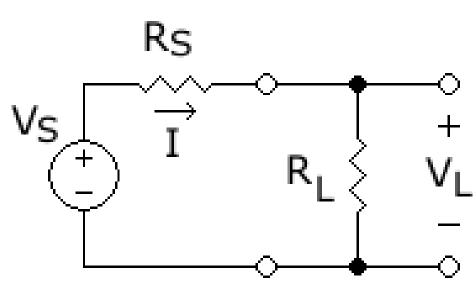



Figure 4.8: PV simple electrical model

This circuit is then analyzed and found that power is maximum when $R_s = R_L$. This analysis can be seen in the below equations.

$$P_L = I^2 R_L \qquad (4.2)$$

$$I = V/(R_S + R_L) \qquad (4.3)$$

$$P_L \, (V/(R_S + R_L))^2 \qquad (4.4)$$

$$R_L = \frac{V^2}{(R_S{}^2/R_L) + 2R_S + R_L} \qquad (4.5)$$

$$\frac{d}{dR_L}(R_S{}^2/R_L + 2R_S + R_L) = \frac{-R_S{}^2}{-R_L{}^2} + 1 \qquad (4.6)$$

$$\frac{R_S{}^2}{R_L{}^2} = 1 \Rightarrow R_S = R_L \qquad (4.7)$$

In Equation (4.5), the load resistance is calculated which, according to Equation (4.2), needs to be maximized to maximize power. Equation (4.6) differentiates the denominator of Equation (4.5) to find the minimum. This will maximize the load resistance. As you can see from Equation (4.7) the maximum load resistance is when it is equal to the source resistance. To find the source resistance, we took maximum power characteristics of our solar panel, which were given by Eco-Worthy. This calculation can be seen in Equation (4.8) below.

$$R_s = V_{MAX}{}^2/P_{MAX} = (18.0V)^2/100W = 3.24 \; Ohms \qquad (4.8)$$

An optimum resistance of 3.24 Ohms was calculated using this method that is very close to what we calculated using the graphical method. In order to maximize power input, we will plan on using a burner somewhere in between these two values. These values are based on perfect solar insolation; with our conditions the resistance will need to be slightly higher than this to maximize efficiency.

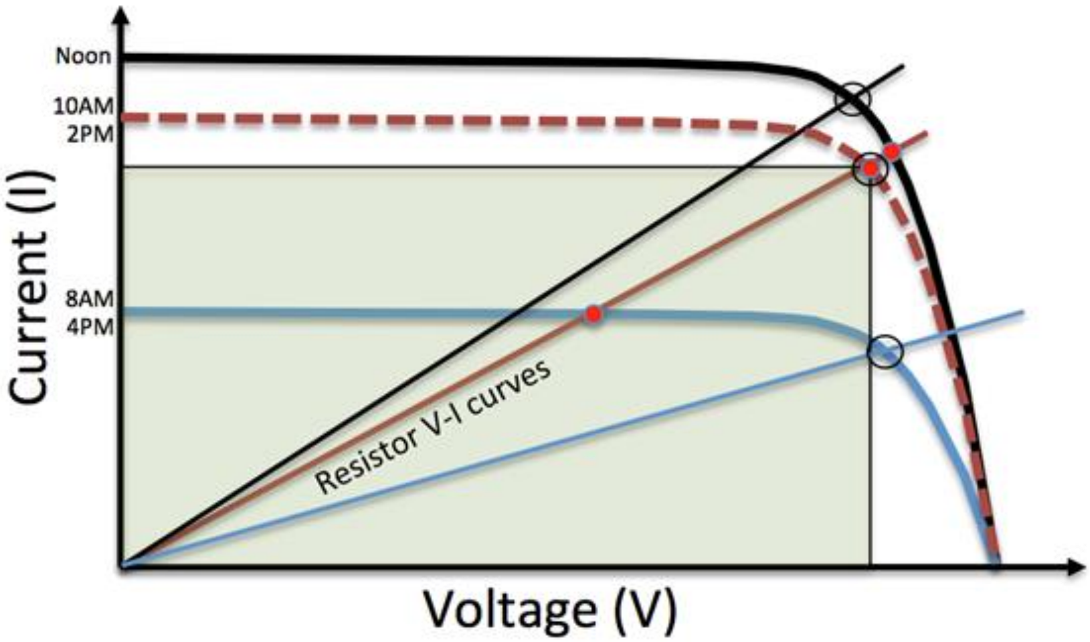



Figure 4.9: Standard solar panel power curve. The operating points for each curve at its optimized resistance are indicated with black open circles while the operating points of each curve at our chosen resistance are highlighted by red dots. Power is equal to the area of an inscribed rectangle defined by the operating points

Figure 4.9 illustrates a typical voltage/current (V-I) curve (solid) for a solar panel under full solar insolation such as a solar panel directly facing the sun at noon. However, when the sunlight is not perpendicular, received solar intensity drops, resulting in a decrease of electrical current. The blue curve illustrates the approximate power output for 8 AM or 4 PM for the same "noon facing" solar panel, corresponding to a 50% reduction in solar intensity. This approximation is only correct for equinox and overestimates the intensity by neglecting the increased amount of atmosphere the sunlight must travel through, although this is a reasonable approximation to illustrate the concept. V-I curves for the entire day between 8 AM and 4 PM fall between the two solid curves. The delivered power (the area of the shaded inscribed rectangle) depends on the operating point on the curve, defined by the intersection of the curve with the $I = V/R$ line of the resistor (straight lines shown in black, red, and blue for increasing resistances - in practice, the resistance will increase with increased temperature, which would increase with increased power, so the lines will not be straight, but have a slight downward curvature. The straight-line approximation serves to illustrate the concept). Thus the resistance of the heating element is crucial to maximize the delivered power. The resistance that maximizes noon sunlight is lower than the resistance that maximizes 8AM/4PM sunlight. A resistance that optimizes the delivered power throughout the day will strike a compromise between the 2 solid curves. The resistance that optimizes power for 10 AM/2 PM sunlight at 87% of the maximum solar intensity will likely optimized the system over the course of the entire day.

### 4.10.2 - Heat Transfer Analysis

We have performed a steady-state heat transfer analysis on a model of our design. The cooker is modeled as a cylinder with a hollow center and ventilation. A 1-Dimensional heat transfer in the radial direction was calculated at steady state to determine the heat loss with different insulation types and sizes. This calculation can be seen in Appendix D. The model is assumed to have an internal temperature of 100 °C (the boiling temperature of water) and an external temperature of 25 °C. All sizes are estimates, and can be changed depending on necessary insulation and packaging constraints. These sizes, as well as thermal conductivities, and temperature differences can be adjusted in the excel sheet. Our heat transfer calculations tell us how much heat (in Watts) will be theoretically lost through the insulation and thus is the minimum heat required to boil at steady state.

We took the sizes and chosen insulation to model this heat transfer in a finite element analysis (FEA) for our final design. The model is shown in Figure 4.10 and analyzes the insulation for the cooker. The interior cylinder is held at a constant temperature of 100°C to simulate boiling water while the outside edge is subject to natural convection at 25°C and a convection coefficient of 25 $W/m^2K$. The bottom of the interior section models the burner where 100W of power is introduced to the system from the solar panel. This FEA model shows a very high temperature region just below the burner. We decided to add extra insulation of a non-flammable material (such as clay or ceramics) below the burner to help prevent the straw below the burner from getting this hot because it's combustion is less than is shown in our FEA model. We don't expect the solar cooker to ever actually get this hot though for a number of reasons. This model is at steady state which means it has been running for an infinite amount of time. Our cooker will run a maximum of 12-14 hours per day simply based on the hours of sunlight. Also, during the time that the cooking is running, we will not always be getting 100W of power out of the PV panel. Full power will only be received during peak hours of the day around, 11am-3pm. For the remainder of the day, the power output will be based on the amount of incident light received by the PV. Other factors will come into play as well regarding the power output of the solar panel including the weather on a given day and the presence of dust, pollution, and other particles in the air.

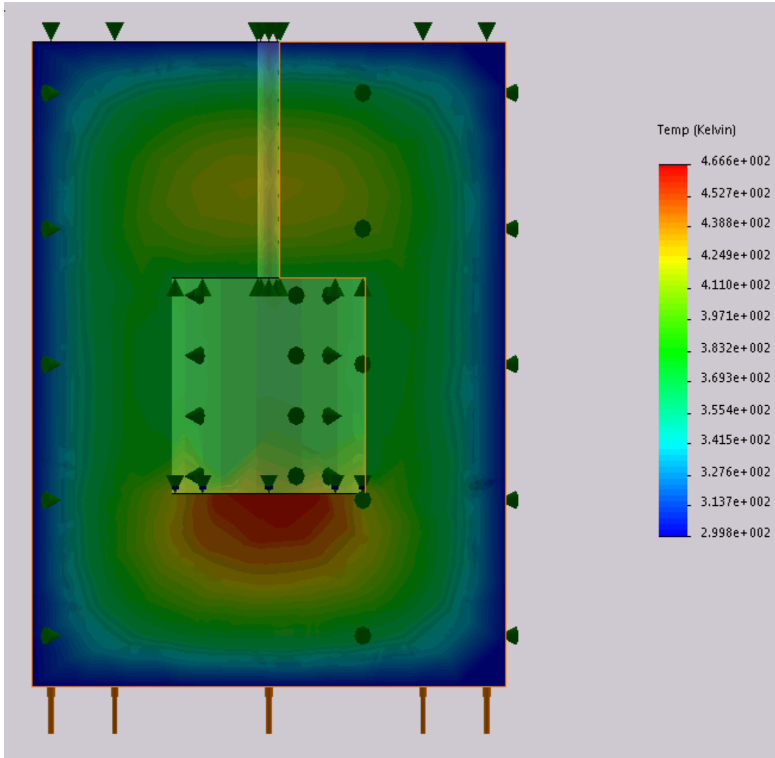



Figure 4.10: FEA heat transfer model

### 4.10.3 - Transient Thermal Modeling

Transient modeling requires a computer mesh analysis and iteration at every point of the insulation. However, it may be more instrumental to use a simplified cylindrical model to represent our system. We use the thermal resistance equation (eq. 4.9) where P is the rate of heat loss; is the difference in temperature between the inner and outer surface; and R is the thermal resistance.

$$P = \frac{\Delta T}{R} \tag{4.9}$$

We model the heat flowing through the insulation in three sections: The cylindrical wall and the two discs above and below the cooking chamber (Fig. 4.11). The cylinder is approximated as a section from an infinitely long cylinder yielding a resistance of:

$$R = \frac{ln(r_2/r_1)}{2\pi\lambda L} \tag{4.10}$$

where $r_1$ is the inner radius of the insulation; $r_2$ is the outer radius; R is the total thermal resistance; λ is the thermal conductivity of insulation material, and L is the length of the cylinder.

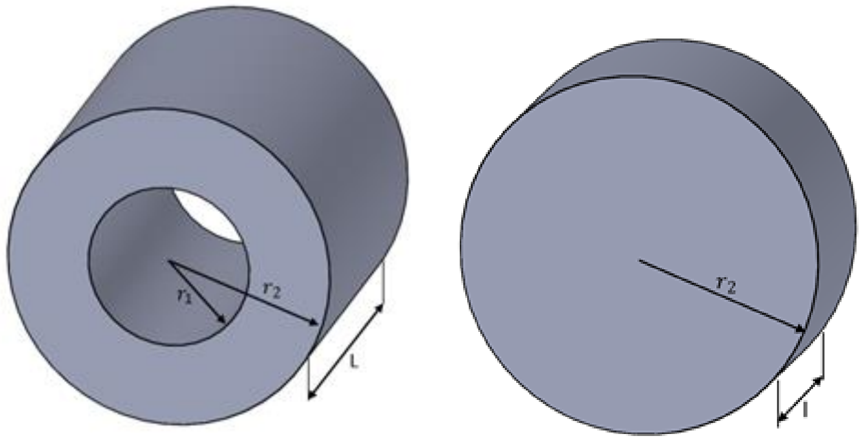


Figure 4.11: Cylindrical geometry for heat loss analysis

Similarly, we can estimate the insulation end pieces as solid disks of radius $r_2$ and thickness *l*, which we set equal to the cylindrical wall thickness ($r_2$ - $r_1$), yielding the resistance,

$$R = \frac{r_2 - r_1}{\pi \lambda r_2^2} \tag{4.11}$$

Thermal resistances are added by taking the inverse of the sum of the inverses. The three sections of insulation combine to give a total thermal resistance of 0.213 K/W, with an inner radius of 0.1778 m, an outer radius of 0.2875 m, and estimated thermal conductivity of 0.06 W/m-K for straw. These equations are used to calculate the rate of heat loss (eq. 4.9).

*Heating*
Our computer model calculates the temperature of the chamber every minute, assuming uniform temperature of the contents and of the outside environment.

The amount of energy present in the system is used to find the difference in temperature between the inside and outside of the insulation. By subtracting the heat loss (eq. 4.9) from the power provided by the solar panel, the amount of energy is updated to the next time increment:

$$E_n = E_{n-1} + (P_{in} - P_{loss}) \times t_{step} \tag{4.12}$$

Where $E_n$ represents the energy in the chamber at a certain moment in time; $E_{n-1}$ represents the energy at the previous timestep; $P_{in}$ is the power received from the

solar panel; $P_{loss}$ is the heat loss rate (4.9); and $t_{step}$ is the time between calculations. ΔT is found from the equation 4.13.

$$E_n = mC\Delta T \tag{4.13}$$

Manipulating equation 4.13 to further suit our model, we can solve for the temperature change using equation 4.14,

$$\Delta T = \frac{E_n}{(mC)_{h20} + (mC)_{mass}} \tag{4.14}$$

where $E_n$ is the total energy from equation 4.12; m is the mass; and C is the specific heat. The denominator is separated into 2 parts, one for the water that is being heated, and another for various other masses that are present in the system. These include potential thermal storage, the pot, and any interior structure of the cooker. This model will be used later on to compare our results during testing.

## 4.11 - Safety Considerations

Safety is very important in the implementation of photovoltaic cookers in Africa. One of the main reasons for this project was to increase the safety of cooking; we need to ensure that our method is much safer than previous methods. Since we have removed the harmful emissions from conventional cooking methods, it should already be relatively safe, however there are some other safety factors to consider now.

One safety consideration is the combustion of our insulation. As shown in Figure 4.10 above, there is a hot region just below the electric burner. This region in our steady state model is at a higher temperature than the combustion temperature of many of our possible insulated materials such as straw and rice hulls. Obviously the temperatures shown in the figure are exaggerated because they imply that 100W of power will be heating the cooker at all times and it does not take into account that it will cool down overnight. In case the interior temperatures below the burner still do reach near combustion temperatures, we plan on using a non-flammable insulation directly below the burner such as ceramics, clay or mud bricks in order to dissipate some of the heat before it reaches the bulk of the flammable insulation. Additionally, a thermocouple controller or temperature dependent switch will be implemented below the burner. This controller will turn off the power from the PV to the burner or simply open the circuit so no power is provided and the temperature of the insulation will be allowed to decrease. During normal use of the cooker this should not be an issue because the water boiling will keep the interior temperatures near 100°C. If left on with no water inside the cooking chamber however this could quickly become a safety hazard.

A second safety issue to consider was the pinch points along the top edge of the cooker's shell. The shell is made from 22-gauge sheet metal (0.034 inches thick) and the lid placed on this shell is less than 15 pounds. The weight of the lid also does not include

any water weight absorbed from evaporation of the boiling water inside of the cooking chamber. If a finger gets caught between the lid and shell while placing (or removing) the lid on the cooker the weight combined with the sharp edge of the shell could easily cut it. To combat this issue, we added rubber tubing along the top edge of the shell.

A third issue we considered was removal of the pot after cooking. This pot will contain food still at or close to 100°C because the food inside has been simmering. It is important that the user can remove the pot without burning themselves. We explore a number of options to prevent burns including different handles and a device to remove the pot with. Ultimately we decided that the most reasonable way to fix this issue was to simply have the user wear oven mitts or let the pot cool to a temperature that will not burn them before removing. Currently people in 3rd world countries are cooking over a 3-stone fire. The handles from the pot will be significantly hotter in their method than ours anyways and they already can remove the pots from the fire without burning themselves. It would not be cost effective for us to implement a method of removal of a hot pot when a cheaper alternative is available.

Our final safety consideration was the fraying of the wires from the PV to the burner. These wires are threaded through a fairly small hole in our sheet metal shell. Similar to the pinch points discussed above, we aim to prevent the wires from being cut by this sharp edge. A rubber grommet is inserted into the wire hole in order to prevent wire fraying at the contact point with the outer cylinder.

The final DFMEA analysis of safety and failure modes can be seen in Appendix F

# Chapter 5 - Product Realization

## 5.1 - Developing World Design

Upon completion of our previously stated design, we realized that it was much too expensive for our third world application. It would be more effective to create a cooking unit that is much simpler and be able to implement more of them with the money we had. The only necessary components are a solar panel, insulation, and a heating element. The solar panel and insulation are already as cheap as they can possibly be (unless solar panels are donated), however the heating element can be made cheaply, and the structure of the cooking unit is unnecessarily robust. Our prototype greatly differs from the previous design to lower our costs and will be shown in the section below.

## 5.2 - Manufacturing Process

### 5.2.1 - Custom Heating Element

A heating element is simply a resistor. We had previously planned on purchasing traditional stove top heating elements, but it could be much cheaper and more efficient to build them ourselves. This allowed the flexibility to choose resistance and shape as well. We used 26-gauge Nickel-Chromium (NiCr) wire (which has a standard resistance of 2.67 ohms/foot) immersed in a concrete tile ½" thick. The left portion of Figure 5.1 shows the wire woven into our mold. The right side of Figure 5.1 shows two finished burners. Note, wires should be clamped together rather than soldered because the solder will melt during burner use.

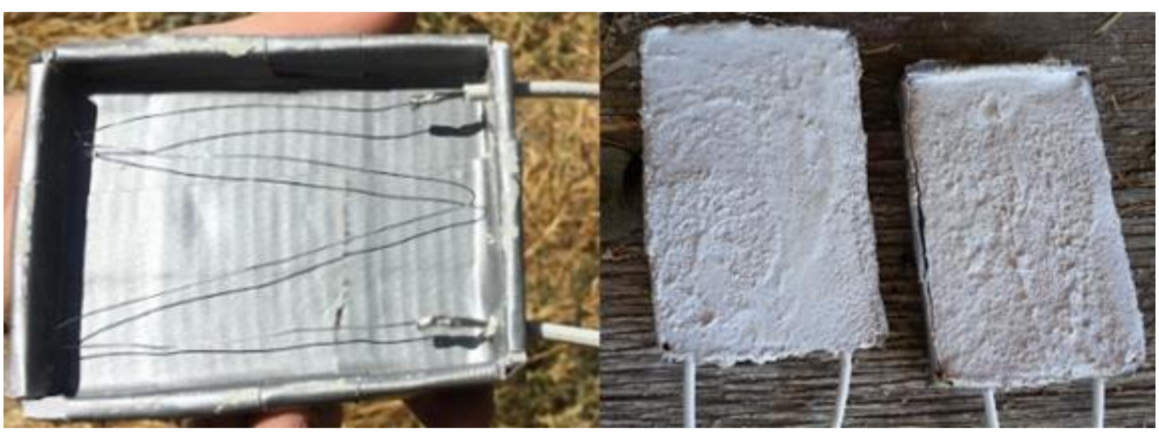


Figure 5.1: Nickel-Chromium Heating Elements. Resistive Nickel Chromium wires are held into place in a mold (left). After concrete hardens, the finished heaters can be used (right).

**5.2.2 - Outside Structure**

The structure to hold our insulation proved to be the most expensive portion of the previous model. We deemed this system to be unnecessary as it's only functionality could be done in a much cheaper way. We decided to build a cooker that was partially underground and above, with the idea stemming from videos depicting Ugandan cooking mostly on the ground in the Baganda and Soroti communities. The following figures show the manufacturing process of this design:

Figure 5.2: The first step was digging a hole which was approximately 3 ft. by 3 ft. and 12 inches deep. Basically, the hole should allow 10 inches of insulation on all sides of the pot, which is the minimum insulation for the desired thermal resistance. The sides of the hole were supported by mud/clay.

Figure 5.3: The dirt from the hole was used to make bricks by mixing mud and straw with a 1:1 ratio. We made a fixture made from plywood and 2x4 to compact and form the mixture into bricks. They were then cut using a saw to roughly 8 inch sections. The bricks were laid out and stacked around the hole so that the total height of the cooker was about 2 feet.

Figure 5.4: To make a countertop, we cut a hole in the middle of a piece of plywood and added two more holes to allow space for the hands to reach into the cooker. The top surface of the plywood was then covered with a wire mesh. A thin layer of cement and sand mixture was spread on the top surface of the counter. We smoothed and textured the top surface by spraying water and flattening the surface with a trowel.

A thin sheet of aluminum can be rolled into a cylinder and lowered into the structure to make an inner cooking chamber and prevent the insulation from falling into this area.

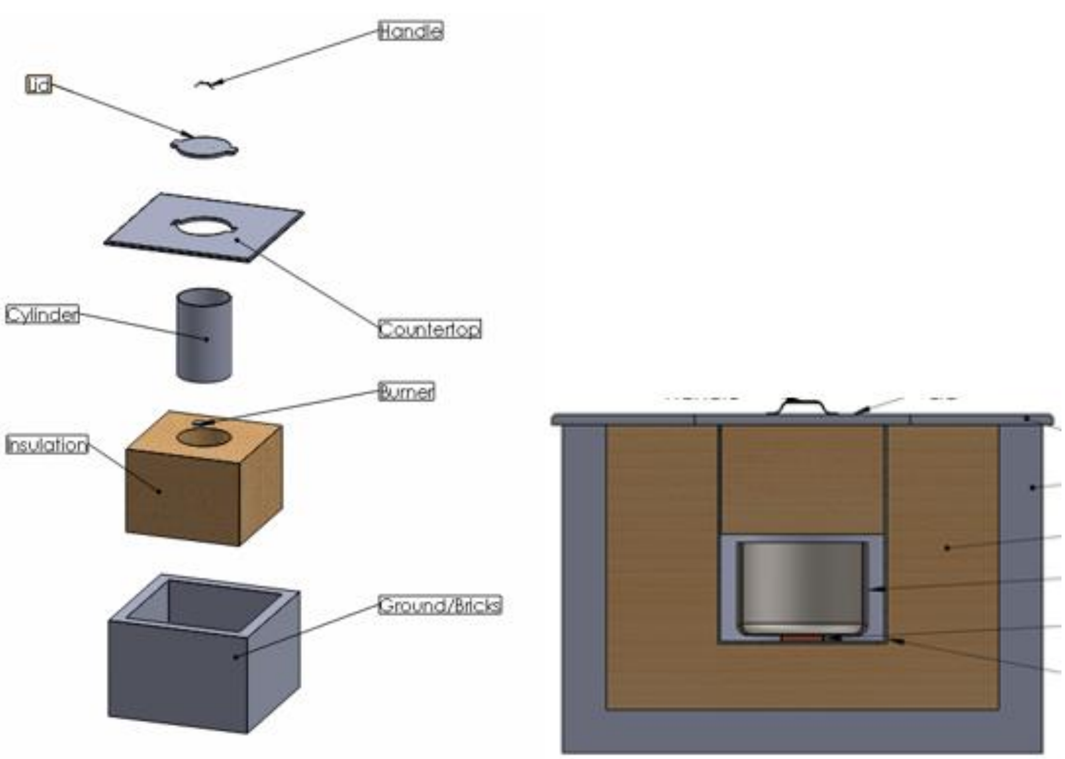



Figure 5.5: Solidworks model of this design

# Chapter 6 - Design Verification

## 6.1 - Testing Plan

In order to test the performance of our prototype, we planned on performing multiple tests. We wanted to perform several experiments at known power inputs so that these tests were repeatable to test different geometries and insulation types if needed. We also wanted to do several real time tests using a solar power.

### 6.1.1 - Repeatable Testing

To ensure that this testing is in fact repeatable, we will have to use a constant 100W power supply. This eliminates the possibility of fluctuations in power like we would have using the solar panel. The power source, supplied by Cal Poly, will be attached to our heating element as if it were the solar panel. 1 L of room temperature water will be added to a pot and placed in the cooking chamber. Thermocouples will be attached to the burner, under the cooking chamber in insulation, and inside the water in the pot. The burner will then be turned on and temperature measurements will be taken every minute from all three thermocouples. This experiment will be done inside to decrease the amount of forced convection occurring on the outer cylinder. The water will be brought to a boil, simmered for 5 minutes, then the burner will be cut off and temperature will be taken until the water cools off to around 100°F. We will do these constant power supply tests using 100W, 75W, and 50W.

### 6.1.2 - Real-Time Testing

We also want to test the oven under realistic condition so we will do testing using the solar panel. This testing will be the same as the repeatable tests with a few additional measurements. We will measure current and voltage so that we can calculate power. We will also use a solar incidence meter so we can further understand what kind of power we can get out of our PV panel in different types of sunlight. These tests will be done at different times of the day and in different cloud coverage's so we can have a wide range of data.

## 6.2 – Testing

Power supply equipment could not be obtained for the repeatable testing at specific powers so these experiments were never carried out. Although this part of the testing was incomplete, we deemed our prototype's performance sufficient through the real-time testing that was completed. This consisted of several different experiments with and without food.

The first experiment consisted of boiling 4 liters of water using a 3.4 ohm burner. This burner was used because we were considering the average maximum power per day obtained from the PV panel rather than the peak maximum power we can achieve from the solar panel; therefore, we needed a higher resistance. This was explained in more detail in Section 4.10.1. The results are shown below.

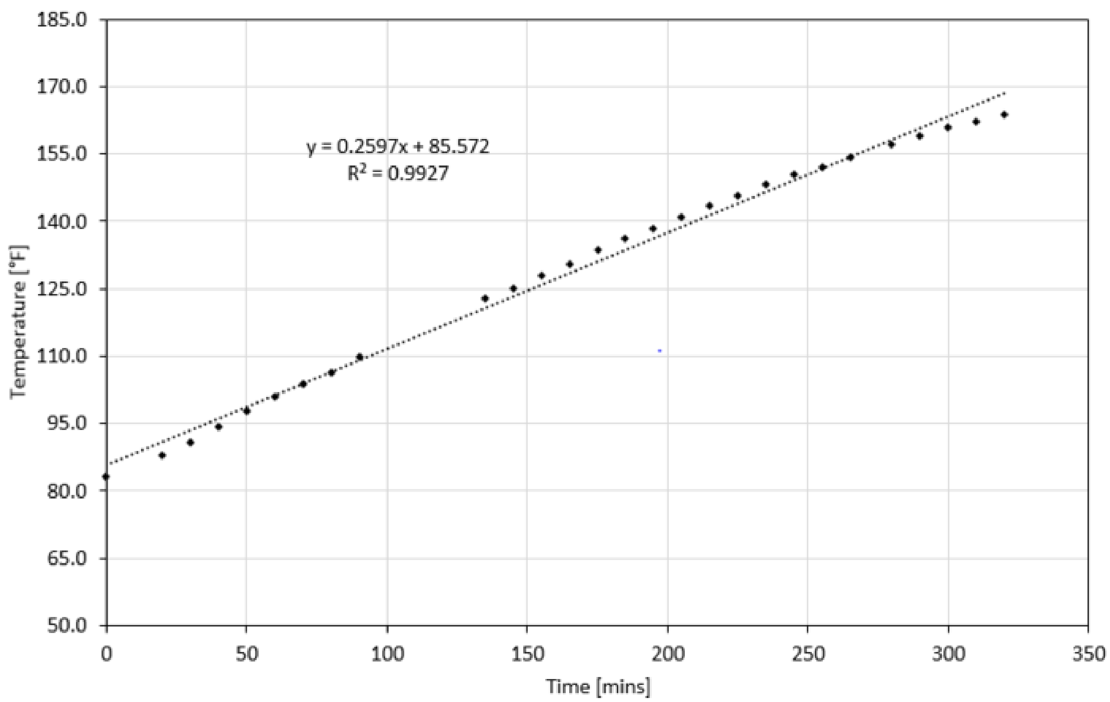



Figure 6.1: Test #1

We started our test around 11:00 am and ended a little over 5 hours of testing. Using a watt meter, the cooker varied between 60-70 watts of electrical input power. For every minute the water would warm up about a quarter of a Fahrenheit, which is acceptable considering that we are using a 100 W solar panel to warm up 4 liters of water and about 5 pounds of cement (inner structure), totaling about 13.8 pounds of thermal storage. Our last temperature reading was 163.7 degrees F. We ended here due to the fact that the power delivered by the solar panel was beginning to become insufficient to boil our water. There needed to be more direct exposure to sunlight in order to power our cooker.

For a second experiment, we decide to cook about 4 liters of chili containing tomato, onion, beans, sauce, and ground turkey. The ground turkey was cooked separately for proper cooking before being added to the chili. We decide to lower our resistance of our burner to 3.1 ohms. The results are shown below.

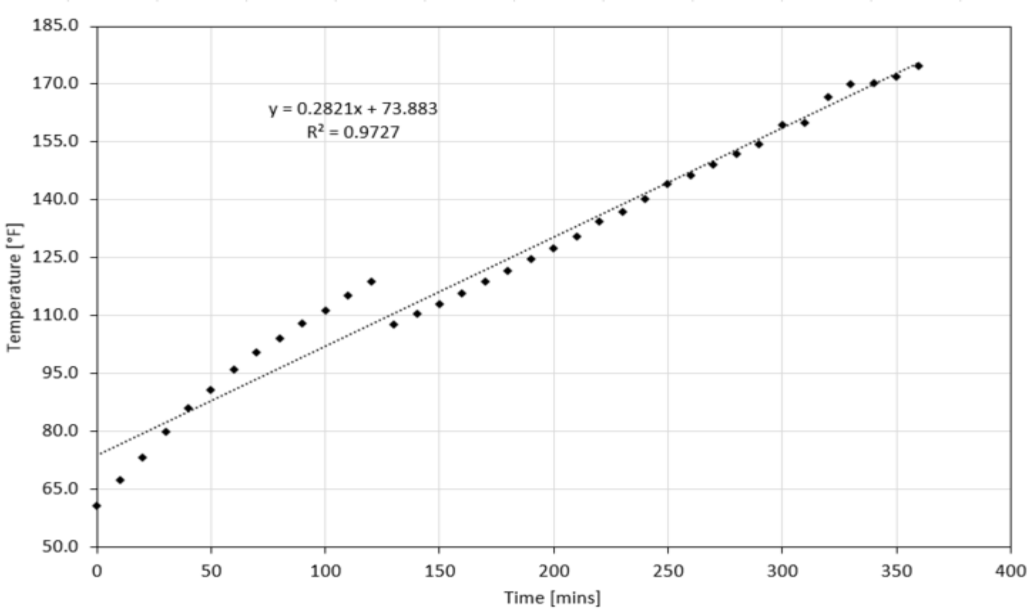



Figure 6.2: Test #2

The 4 liters of food warmed up a bit faster than the previous experiment (heating up the 4 liters of water). Also, the cooker electrical power input varied between 65 to 75 watts, which is possibly due to the fact that we lowered the resistance of our burner. We started cooking around 10:00 AM. We ended after 6 hours cooking with our end temperature being 174.7 degrees Fahrenheit. The disparity in our graph between 100 and 150 minutes was caused by us opening the cooker in order to stir the food to ensure it wasn't going to burn. We decided that with such low power, the chili would not burn and left the lid on for the remaining time. We did however lose around 15 degrees Fahrenheit.

Lastly, we did one more test so we can compare this cooker to our previous cookers. We used the same burner with 3.1 ohms. Again, we had about 65 to 75 watts of electrical power depending on the insolent sunlight. Our results are shown below in Figure 6.3.

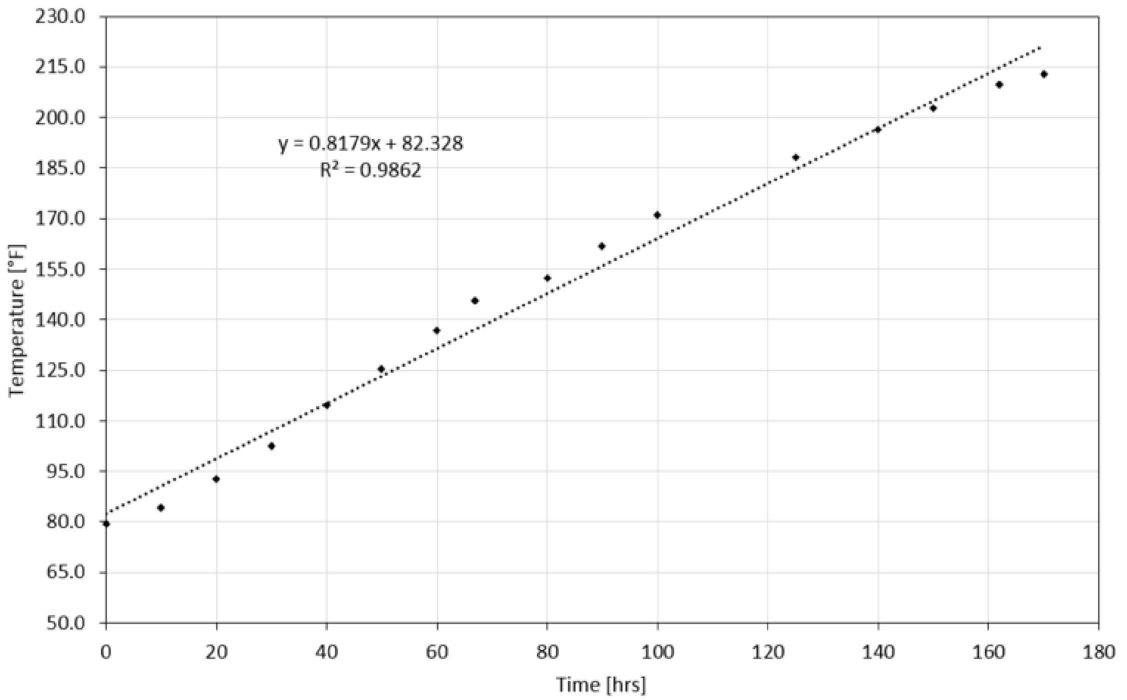



Figure 6.3: Test #3

## 6.3 - Plan for Uganda

Omar and Chris went to Uganda on July 12, 2016 for four weeks with Aid Africa. Through funding from Cal Poly, all materials were bought upon arrival and ovens were built and implemented in villages. With all of the data collected from the second prototype testing, we knew what to expect with the ovens built based off of their geometries, burner resistance, and solar incidence in Africa. Due to materials availability, some changes to the overall design were made. Two separate prototype stoves were built and tested while in Ugandan. Once the superior stove was decided on, two of these stoves were implemented into Ugandan villages. The villagers were shown how to use and fix the ovens if they got broken. Air quality monitors were purchased in the US prior to leaving so that air quality within the villager's homes could be tracked. This gave us data that potentially could be used for carbon funding. Peter Keller as well as other Aid Africa employees frequent this part of Uganda, so the villagers who received the stoves could be checked up on and asked about their opinions on the stoves. The results of the stove implementation are described in detail in Chapter 7.

## 6.4 - Comparison to Thermal Modeling

Figure 6.4 shows the temperature of 1kg of water (1 liter) heated with 3.5 kg concrete forming the inner cylinder of the design shown in Figure 5.5. The red points of the figure are actual data points, and the black line is the model defined in section 4.10.3.

The experimental temperature gain in the beginning is less than that predicted by the model. This may be due to the initial temperature of the concrete enclosure being lower than the initial temperature of the water, or less than ideal sunlight exposure for the solar panel. The model uses an input power of 75 W, which was the average measured output power of the solar panel over the course of the test as measured by a power meter. As the model reaches a boiling temperature, it stops iterating new temperature values and instead outputs 100°C because the water will never exceed this temperature.

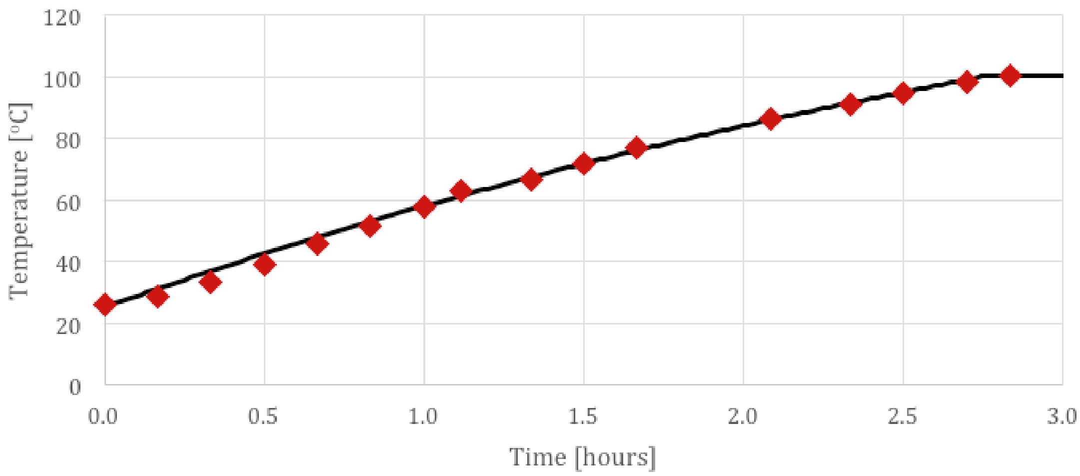



Figure 6.4: Temperature of water over time during heating (red diamonds), compared to the thermal model (black line)

We ended this experiment at boiling, but we can calculate the maximum temperature that the solar cooker could achieve if water is not present (because it has all boiled off, or the stove is left on without anything inside) by setting the heat lost through the insulation equal to the power provided by heater, yielding 185°C or 365°F. This maximum temperature increases with increased thickness and quality of insulation indicating potential risk of combustion if no water is present.

## 6.5 - Power Measurement Calculation

Figure 6.5 displays the temperature of about 2.7 kg of water in the solar cooker of Figure 5.5, brought to a boil and allowed to cool. We can find the relevant power terms through the use of equation 4.13, where $E_n$ is the energy, and □□ is the temperature increase or decrease. Taking the slope of the cooling curve (red line) at 90°C yields a temperature loss rate of 6.67°C/hr, corresponding to thermal loss rate of 20.7 W. Similarly, the 19.2°C/hr of thermal gain at 90°C corresponds to 59.6 W of thermal intake. If you take the sum of these values, you get a total power input of 80.3 W, consistent with our readings of the solar panel output. This value is higher than our average power input of 75 watts because the solar intensity around the time of our measurements was close to the ideal for our heating element resistance.

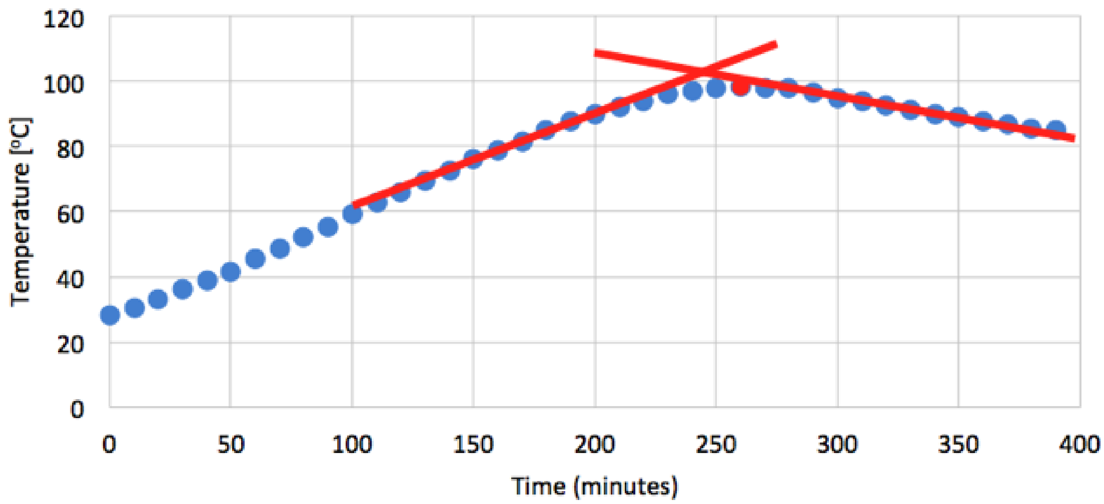



Figure 6.5: Temperature of 2.7kg of water in solar cooker. The heater was turned off at 260 minutes represented by the red data point. Data after this point shows the cooling of the system. The slopes of the red lines indicate the temperature gain/loss over time and are used to calculate power.

# Chapter 7 - Conclusion and Recommendations

## 7.1 - Implementation in Uganda

After receiving the Baker and Koob Endowments for the summer of 2016, our project got the opportunity to implement our design in Ugandan villages. We received enough funding for four students to travel to Gulu, Uganda for four weeks over the summer. This group of students included two students from our project, Chris and Omar, as well as Ian Stone, a physics major, and Madison Fleming, an industrial technologies major. The students were accompanied by Peter Keller, the head of a non-profit Aid Africa who is based out of Uganda. During their four weeks there, the students researched, tested, and implemented solar cookstove technology as well as assisted Aid Africa with their projects.

Once in Uganda, the students realized that the designs previously described in this report were not feasible for implementation in the region they were in. The final design that included mainly metallic parts was priced out by a local metal shop and deemed too expensive by the students. The design that is described in the beginning of this section which consisted of digging into the ground was also deemed infeasible. The students planned on implementing the stoves inside the villagers' huts, which were small and built on hardened clay. This would make it difficult to dig into the ground and fit this into their home. With these limitations in mind the students came up with a new design to implement into the villages. Several prototypes were also built and tested there before implementation.

### 7.1.1 - Technical Design/Specifications

All materials besides wiring for the heating element and the testing devices were purchased locally in Uganda. Prior to the trip Peter Keller of Aid Africa informed the students that all materials needed for the cookstoves could easily be purchased in the town of Gulu, Uganda, where the students would be for the majority of their stay. These materials were purchased at different stores in Gulu where prices and quality varied. The prices shown in Table 7.1 reflect the final price paid by the students for each item, but for future reference these prices may not reflect the average local prices.

Table 7.1: Cost analysis of Ugandan cookstoves

| Material | Quantity | Unit | Unit Cost | Unit Cost | Total Cost | Total Cost |
|---|---|---|---|---|---|---|
| - | - | - | *Shillings* | *$* | *Shillings* | *$* |
| 9mm Rebar | 24 | m | 1583.333333 | $0.49 | 38000 | $11.88 |
| Rebar labor | 1 | | 2500 | $0.78 | 2500 | $0.78 |
| Electrical Tape | 1 | Roll | 1000 | $0.31 | 1000 | $0.31 |
| Rice Husks | 2 | Bag | 2000 | $0.63 | 4000 | $1.25 |
| Switch | 1 | EA | 10000 | $3.13 | 10000 | $3.13 |
| 1.5mm Wire | 5 | m | 3000 | $0.94 | 15000 | $4.69 |
| Saucepan | 1 | EA | 7000 | $2.19 | 7000 | $2.19 |
| Reed Mat | 1 | EA | 2500 | $0.78 | 2500 | $0.78 |
| Rope | 1 | EA | 500 | $0.16 | 500 | $0.16 |
| 120W Solar Panel | 1 | EA | 320000 | $100.00 | 320000 | $100.00 |
| Concrete | 1 | kg | 500 | $0.16 | 500 | $0.16 |
| High temp wire | | | | | | |
| Nichrome wire | 10.5 | in | | | | |
| **Total** | | | | | **401000** | **$125.31** |

As you can see in Table 7.1, each stove cost around $125 including the solar panel. With the solar panel costing around $100 (less than $1 per Watt), the remaining materials were only about $25. The solar panel purchased was a 120W polycrystalline panel produced by Sunshine Solar (Model AP-PM-120). The panel's statistics can be seen in Table 7.2.

Table 7.2: Solar panel statistics

| Statistic | Quantity |
|---|---|
| $P_{max}$ | 120W |
| $I_{mp}$ | 6.85A |
| $V_{mp}$ | 17.5V |
| $I_{sc}$ | 7.67A |
| $V_{oc}$ | 22.05V |

These statistics were tested by the students using a multimeter and were deemed fairly accurate. The students used these given statistics to design an optimum heating element for the cookstoves. Four separate heating elements were built, two of which were prefabricated by the other students at Cal Poly. Since the prefabricated elements were designed for a 100W solar panel their resistances were too high so others had to be built. These heating elements had a resistance of 2.5 Ohms. Several geometries of the heating element and configurations of the Nichrome wire were tested. The square mold with a zig-zag design was found to be the best suited for the stove since the heat was evenly distributed throughout the heating element. The high temperature fiberglass and copper wire attached to the heating element could withstand temperatures up to 500°C. This was a critical part of the design in order to ensure that the wire did not melt. The final mold for the heating element was created and shown in Figure 7.1. Figure 7.2 shows the heating element once the cement and sand mixture has dried and hardened.

Figure 7.1: Ni-chrome wire configuration of the heating element

Figure 7.2: Dried heating element

Once the heating elements were tested, the students built two separate prototypes in their office in Gulu for testing prior to implementation. The first prototype consisted of two separate burlap sacks containing rice hulls, one for the base of the stove the other for the top. This was similar to the initial “hay bale” conceptual design. As pictured in Figure 7.3, a circular hole with a diameter slightly larger than the diameter of the pot being used was cut in the base. Mesh wire was laid and mudded in so that the rice hulls would not fall out of the base. Small wooden supports were placed at the bottom of this to hold the heating element flush against the pot. Once the pot was placed on the heating element, the other burlap sack would be placed on top of the pot to cover the pot and base of the stove to retain heat.

Figure 7.3: Burlap sack prototype

This prototype was tested twice. The first test was not recorded due to insufficient sunlight. Test #2 was completed on July 26th, 2016. One and a half cups of local peas were boiled in two and a half cups of water starting at noon. The test lasted around five hours, its longevity due to inconsistent sunlight and rain. Temperature inside the pot was

recorded every thirty minutes using a thermocouple while power measurements were taken every thirty seconds using an Arduino data logger. Figure 7.4 shows the temperature of the food graphed over the power output of the solar panel throughout the test. The gap in the temperature data was during a rainstorm where the panel and logger had to be brought inside. As you can see from the figure, the hottest the stove got up to was around 144°F. The slope of the temperature data was calculated during these two periods of more consistent sunlight in order to compare the rate of temperature change of this prototype to the other.

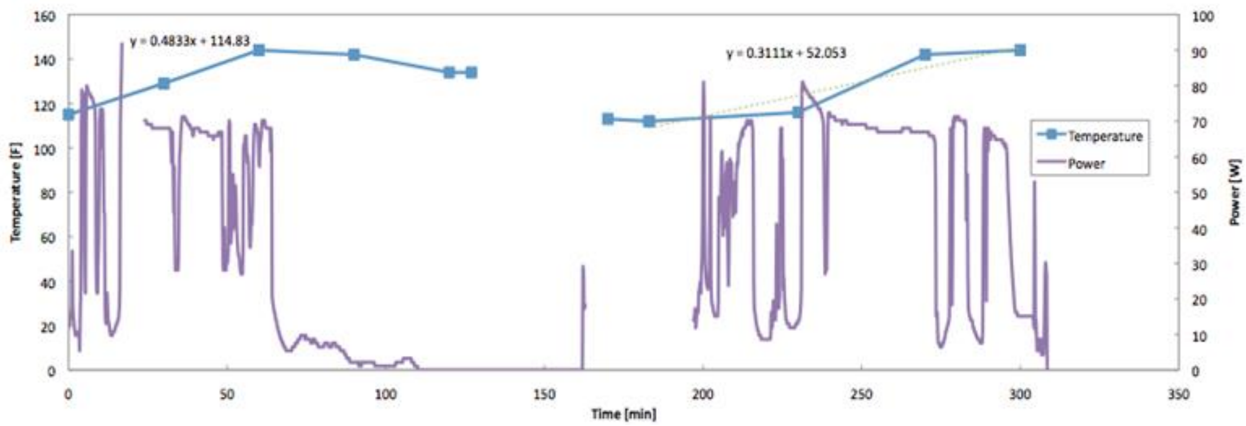



Figure 7.4: Burlap sack prototype test #2

This design was not implemented into any villages due to its low durability. The students thought that if the stove needed to last around 10 weeks with several uses a day then this design would not be feasible.

The second prototype built and tested had a much different design. It consisted of two separate parts: the outer cylinder and the inner cook chamber. To form the outer cylinder a locally bought reed mat was used in order to keep the rice hulls contained. The mat was held up by pieces of 9mm rebar hammered upright into the ground in a circular formation. Once the reed mat was placed upright and woven through these rebar uprights, the mat was tied together end to end and an additional two support ropes were tied around the entire cylinder to keep it from bulging under the weight of the rice hulls.
The inner cooking cylinder was built out of an aluminum cooking pot with a hole cut in it for the wiring of the heating element. This inner chamber was dimensioned so that the cooking pot being used had a slightly smaller diameter allowing it to fit snuggly into the cooking chamber. This decreases the chance of free convection within the cooking chamber. The cooking chamber was also shorter than the cook pot so that after the food is cooked it can easily be removed from the cook chamber. Once assembled, the inner cooking chamber was placed directly in the middle of the outer cylinder, as seen in Figure 7.5.

The inner cook chamber's diameter allows 8 inches of room for insulation between it and the outer reed mat cylinder. To elevate the cooking chamber and allow

room for insulation under the cook chamber, three rebar supports were tied onto the outer part of the chamber. These rebar supports were dimensioned to allow 8 inches of insulation directly under it.


Figure 7.5: top view of reed mat design

This prototype was tested five times but only the two initial tests were recorded. Both have temperature data but only the first has power data, which is limited within this test. These two tests can be seen in Figure 7.6 and Figure 7.7.

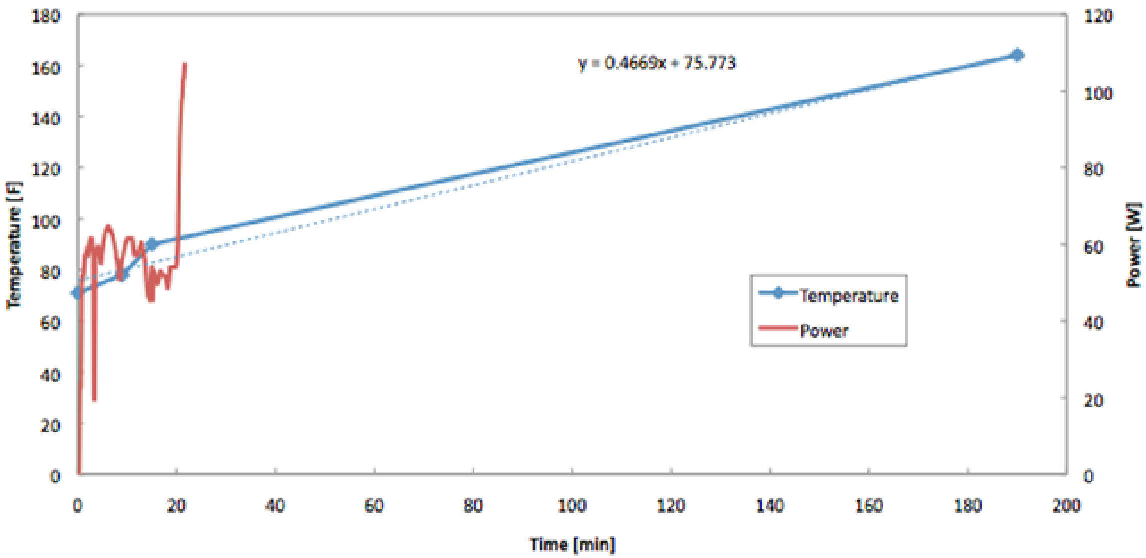



Figure 7.6: Reed mat prototype test #1

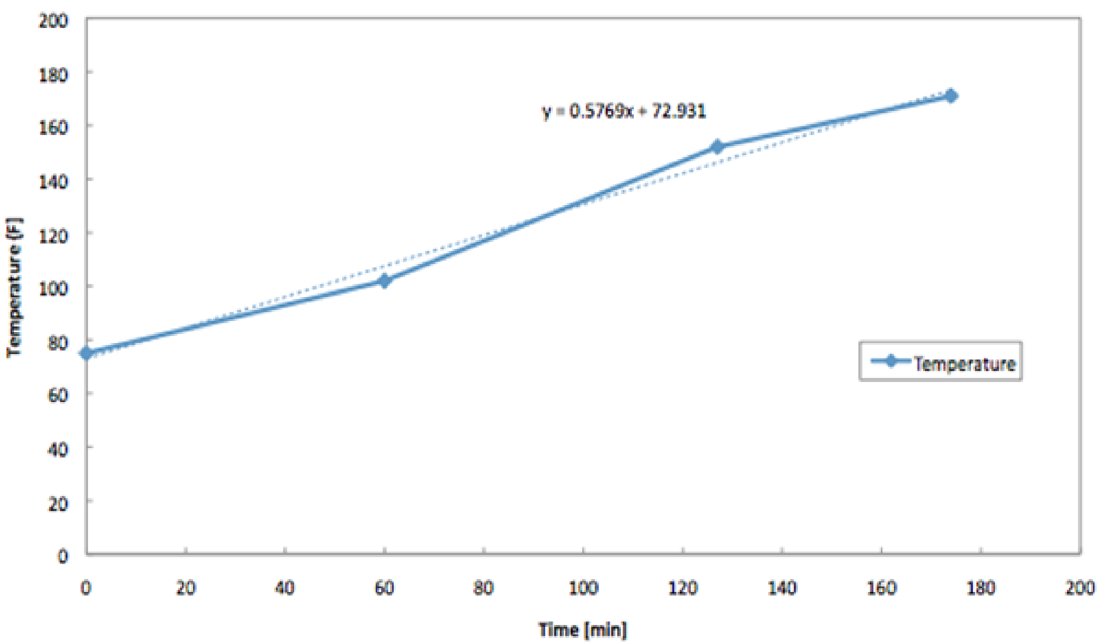



Figure 7.7: Reed mat prototype test #2

Although it is a very environmentally affected variable, the average rise in temperature over time was taken from all of the prototype tests and tabulated in Table 7.3 to compare these two prototypes.

Table 7.3: Prototype test coefficients

| Test # | Burlap Sack Design | Reed Mat Design |
|---|---|---|
| - | *[°F/min]* | *[°F/min]* |
| 1 | 0.4833 | 0.4669 |
| 2 | 0.3111 | 0.5769 |
| **Average** | **0.3972** | **0.5219** |

As you can see from the table the second prototype had a higher rate of change in heat, making it a more efficient oven. Also due to its durability and more aesthetically pleasing design, this prototype was chosen to be implemented into the village huts.

### 7.1.2 - Implementation Strategy

The group of research students worked closely with a non-profit organization, Aid Africa. Aid Africa is located in Gulu, a city in Northern Uganda and their primary projects focus on tree distribution, clean-water wells, and improved cookstove distribution. The students were put into contact with the president of the organization, Peter Keller, who gave them all the necessary resources and information they needed for the trip.

Once in Uganda, the students first visited the villages to see what the current cooking situation is like. Once they got an understanding for the logistical cooking constraints that are common within the Ugandan villages, they began reiterating their solar electric cookstove design to fit the witnessed needs of the village women. As previously mentioned, the students purchased all the necessary materials for the solar stove in Gulu. This is an important point which supports the long term sustainability of their stove given that the necessary materials are readily and inexpensively available within this specific region. The previous design work for this project was deemed infeasible due to the cost of metal. That is why a cheaper design was chosen.

Once the group had chosen the reed mat design that they felt would fit the needs of the end users in the villages, they were ready to install the solar electric stoves. The implementation of the solar cookstoves involved all four students as well as a translator. The students made sure to explain the basic principle of the solar electric cookstove, the potential uses for the stove, and the proper maintenance/upkeep for the stove. One key emphasis made was that the solar electric stove could be used to completely cook a raw meal or, if time or weather was an issue, it could be used as an insulated cooker that does not require energy from the solar panel. This would mean the women could briefly heat up food with their traditional cookstove and then transfer it to the insulated cook chamber of the solar electric stove for it to continue cooking without the use of additional fuel or energy. Furthermore, the students asked that the women help them in building the stove: hammering the rebar supports into the ground, building the outer cylinder, laying the rice hulls, cleaning the solar panel. The students thought the women may have more pride and

understanding for something that they also put work into building. Lastly, the students emphasized that those who used the implemented solar electric stove could adapt the design to fit their needs as they saw fit. The students only hoped that the villagers would share with them their thoughts regarding the stove's design, both positive and negative, as well as any adaptations that they made to the stove for enhanced usability or efficiency.

### 7.1.3 - Air Quality Improvement

One of the biggest benefits for users in the design of new improved cookstoves is air quality. These new stoves are meant to burn fuel more efficiently, or not burn any at all. While one of the reasons may be to reduce or eliminate the need for a large amount of fuel, the other is to keep particulate matter out families' homes, eyes, and lungs. With 4.8 million people dying from causes directly related to particulate matter, it is no trivial problem. The solar electric stove provides an emission-free way to cook, eliminating any irritants and carcinogens from the air. On their research trip, the students wanted to record their progress, so they brought an array of air-quality monitors. The students implemented those monitors into the two homes in which they installed their solar cookstoves. From those monitors they collected data from before and after they installed the stove. The data they collected implied that the families cooked with their traditional stoves about a quarter of the time as they did prior to the solar stove being installed.

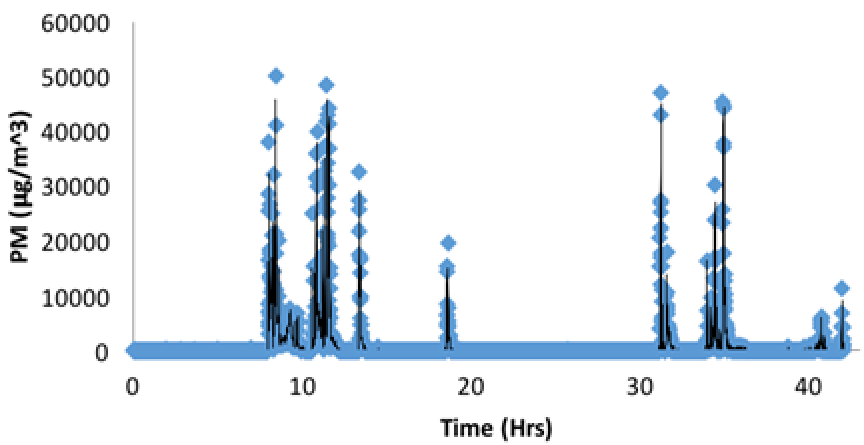



Figure 7.8: Pre-stove installation particulate matter

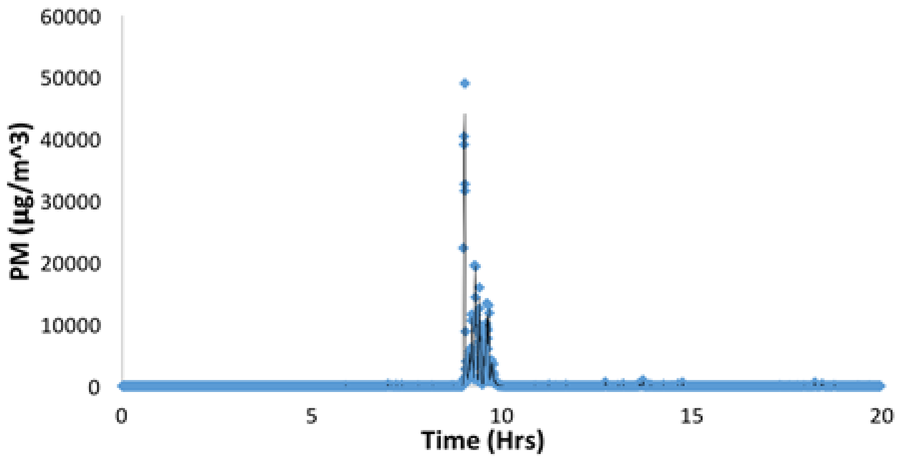



Figure 7.9: Post-stove installation particulate matter

Although the data is promising, since the students could only record about 80 total hours of data there are variables that could affect the data. Placing air monitors and solar panels in a house was essentially giving them something incredibly valuable which prompted the families to lock their doors and keep them closed more often. This in turn means there is less fresh air circulating through the house. Another concern would be that the families would use the stove in the beginning since it is in the beginning a novelty item and are curious as to how it works. To get truly relevant data it would be ideal to have a monitor on site for at least a month, not four days.

### 7.1.4 - Results

The villages that the students implemented the solar electric cookstoves in were located in very remote parts of Uganda where phone and other telecommunications are rare. This highlights another salient reason for the students' partnership with the local Ugandan non-profit, Aid Africa. The students were able to keep track of the progress and adoption of their solar electric cookstoves by having the Aid Africa team make periodic check-ins to the villages. On the most recent field check-in, the Aid Africa staff gave the following report following their direct field visit:

"Hi all, Here's your subject with your cooker. We visited her yesterday and she tells us they've used the cooker every day. They cooked beef in about 3.5 hours and they've cooked rice, okra and eggplant. Then, there's was enough daylight left to heat water for bathing. Don't underestimate the significance of that. They would never waste precious firewood on an extravagance like bathing water. We all like our hot baths; they do, too. One note: the water was too hot and they had to dilute it. You've made a significant improvement in their lives. Staff will return periodically to check on the cookers. No one was at the other homestead but the father came by to unlock the hut and tell us that whenever they are home, they use the cooker. We saw that the panel was there and was

kept clean. I asked them to think about how the cooker could be made better and this family had a ready answer. They want a battery system to charge cell phones and to use a light. Again, on behalf of these families whose lives you have impacted, thank you!"

Figure 7.10: Recipient of the first solar cookstove

The students, whom have since returned to the United States, plan to keep in close contact with the Aid Africa staff and look forward to more updates about the use of their solar electric stoves as well possible design modifications that could be used to enhance its utility in this type of rural setting.

## 7.2 - Future Recommendations

The Cal Poly students who travelled to Uganda have had an incredibly educational and enlightening experience on their research trip to test the solar electric stove in Uganda, one of its potential end markets. After witnessing the living and cooking conditions of those living within rural and urban setting in Uganda, the students envision a large need and potential fit for the solar electric cook stove. Especially after receiving a positive review from the villagers using the cookstoves, the students are hopeful that this technology could be spread to other parts of the world and adapted to help combat similar issues of indoor cooking pollution and environmental degradation.

The students understand that implementation of the solar electric stove in different regions around the world will necessitate alternative designs which are made

from different available materials and with varying cultural parameters. However, the product design modifications are expected to vary on region and should not increase the price or change the utility of the solar electric stove drastically. In order to streamline the design process, a guideline for different design variables such as insulation thickness and burner resistance was created. This will allow anyone to go into a different region of the world and easily design a solar cooker out of completely different materials and yield the same performance results. This guideline is seen in Appendix H.

Additional add-ons have also been considered for our current design. Future additions may include battery-LED light systems and cell phone charging. Ugandan users seemed to show interest in both of these add-ons when asked. A microcomputer may be important to control the cooking, manage electrical power, record performance data, such as temperature and power output. Future challenges are electronic control of cooking, switching power to electronics, logging use for carbon market verification, and development of remote financing methods whereby users pay daily for the use of electronic products.

Another point of interest that has developed as implemented stoves are being used further is the use of the cooker to heat water for bathing. Hot baths are a luxury that are often taken for granted by Americans. Giving villagers this luxury especially in colder climates could drastically improve their lives. Going forward, we may want to branch off from an oven to specifically a water heater.

Immersion heaters are currently being researched by students at Cal Poly for use in solar cookers similar to ours. These heaters could be more efficient than the heating elements we used due to the decrease in heat lost to the base of the inner cooking chamber. Further research needs to be done for this to be confirmed but this may be another design to consider in the future.

# Appendix

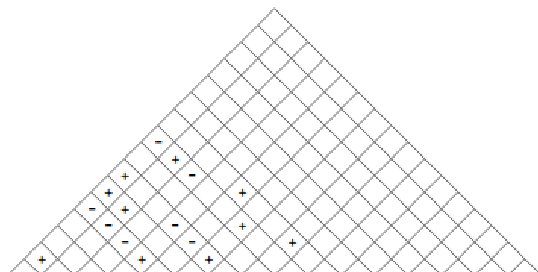
## Appendix A - QFD

QFD: House of Quality
Project: Photovoltaic Cooker
Revision:
Date:

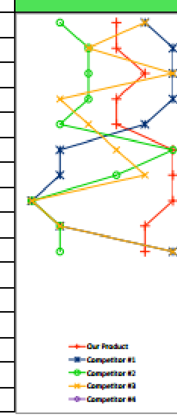
| Correlations | |
|---|---|
| Positive | + |
| Negative | − |
| No Correlation | |

| Relationships | |
|---|---|
| Strong | ● |
| Moderate | ○ |
| Weak | ▽ |

| Direction of Improvement | |
|---|---|
| Maximize | ▲ |
| Target | ◇ |
| Minimize | ▼ |

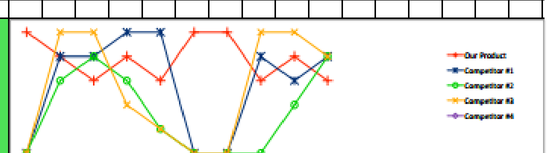


| | | | | | | | | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Direction of Improvement | ◇ | ▼ | ◇ | ◇ | ▼ | ◇ | ◇ | ◇ | ◇ | ◇ | NOW: Current Product Assessment - Customer Requirements | | | | |
| Row # | WHO: Customers: Weight Chart | Relative Weight | User (African Villagers) | Manufacturer | The UN | Non-Profit | Maximum Relationship | HOW: Engineering Specifications / WHAT: Customer Requirements (explicit & implicit) | 100W PV panel | Boil 1L of water in 50 minutes | Safely withstands hot temp. | Low tolerances | Can be assembled in village by 2 people | PV operates close to max efficiency (dry season) | Voltage switch to thermal/electrical storage | Operated by one person | Maintains a simmer temp throughout day | Easy to take food in and out of | Our Current Product | Current Methods (Three stone stove) | Solar Concentrator | Conventional cooking | Row # |
| 1 | | 10% | 9 | 1 | 0 | 9 | 9 | Easy to use/install | ○ | ○ | ▽ | ● | ● | ▽ | ○ | ● | ○ | ● | 3 | 4 | 1 | 4 | 1 |
| 2 | | 14% | 8 | 5 | 0 | 9 | 9 | Low cost | ● | ○ | ○ | ● | ● | ▽ | ○ | ▽ | ▽ | ▽ | 3 | 5 | 2 | 2 | 2 |
| 3 | | 4% | 9 | 0 | 0 | 0 | 9 | Cooks their culture's food | ▽ | ● | ▽ | ▽ | ▽ | ○ | ▽ | ▽ | ● | ▽ | 4 | 5 | 2 | 5 | 3 |
| 4 | | 14% | 3 | 9 | 0 | 5 | 9 | Low tech manufacturing | ○ | ○ | ▽ | ● | ● | ▽ | ● | ▽ | ▽ | ▽ | 3 | 5 | 2 | 1 | 4 |
| 5 | | 7% | 9 | 0 | 0 | 5 | 9 | Low maintainance | ○ | ▽ | ● | ○ | ● | ▽ | ○ | ○ | ▽ | ▽ | 3 | 4 | 1 | 2 | 5 |
| 6 | | 17% | 3 | 0 | 9 | 0 | 9 | Reduce carbon footprint | ● | ▽ | ▽ | ▽ | ▽ | ● | ○ | ▽ | ○ | ▽ | 5 | 1 | 5 | 3 | 6 |
| 7 | | 7% | 9 | 0 | 0 | 5 | 9 | Saftey | ○ | ○ | ● | ▽ | ▽ | ▽ | ▽ | ○ | ▽ | ● | 5 | 1 | 3 | 4 | 7 |
| 8 | | 14% | 0 | 3 | 5 | 4 | 9 | Utilize excess PV energy | ● | ▽ | ▽ | ▽ | ▽ | ● | ● | ▽ | ● | ▽ | 5 | 0 | 0 | 0 | 8 |
| 9 | | 10% | 0 | 5 | 0 | 8 | 9 | Compact shipping | ○ | ▽ | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ▽ | 4 | 1 | 1 | 1 | 9 |
| 10 | | 4% | 9 | 0 | 0 | 0 | 9 | Can be used multiple times a day | ○ | ○ | ▽ | ▽ | ▽ | ● | ● | ○ | ● | ○ | 4 | 5 | 1 | 5 | 10 |
| 11 | | 0% | | | | | | | | | | | | | | | | | | | | | 11 |
| 12 | | 0% | | | | | | | | | | | | | | | | | | | | | 12 |
| 13 | | 0% | | | | | | | | | | | | | | | | | | | | | 13 |
| 14 | | 0% | | | | | | | | | | | | | | | | | | | | | 14 |
| 15 | | 0% | | | | | | | | | | | | | | | | | | | | | 15 |
| 16 | | 0% | | | | | | | | | | | | | | | | | | | | | 16 |




| HOW MUCH: Target | 100W PV panel | Boil 1L of water in 50 minutes | Safely withstands hot temp. | Low tolerances | Can be assembled in village by 2 people | PV operates close to max efficiency (dry season) | Voltage switch to thermal/electrical storage | Operated by one person | Maintains a simmer temp throughout day | Easy to take food in and out of |
|---|---|---|---|---|---|---|---|---|---|---|
| Max Relationship | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Our Product | 5 | 4 | 3 | 4 | 3 | 5 | 5 | 3 | 4 | 3 |
| Current Methods (Three stone stove) | 0 | 4 | 4 | 5 | 5 | 0 | 0 | 4 | 3 | 4 |
| Solar concentrator | 0 | 3 | 4 | 3 | 1 | 0 | 0 | 0 | 2 | 4 |
| Conventional cooking | 0 | 5 | 5 | 2 | 1 | 0 | 0 | 5 | 5 | 4 |
| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

Current Product Assessment - Engineering Specifications

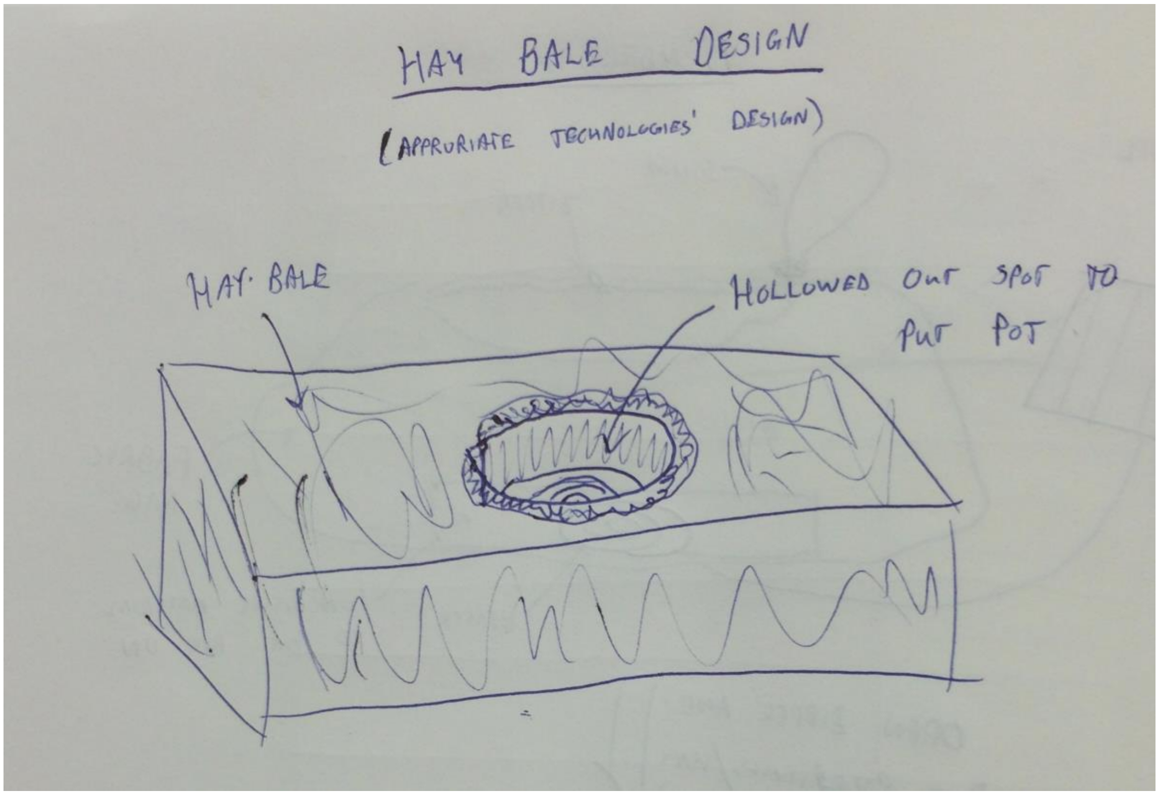



Column # 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

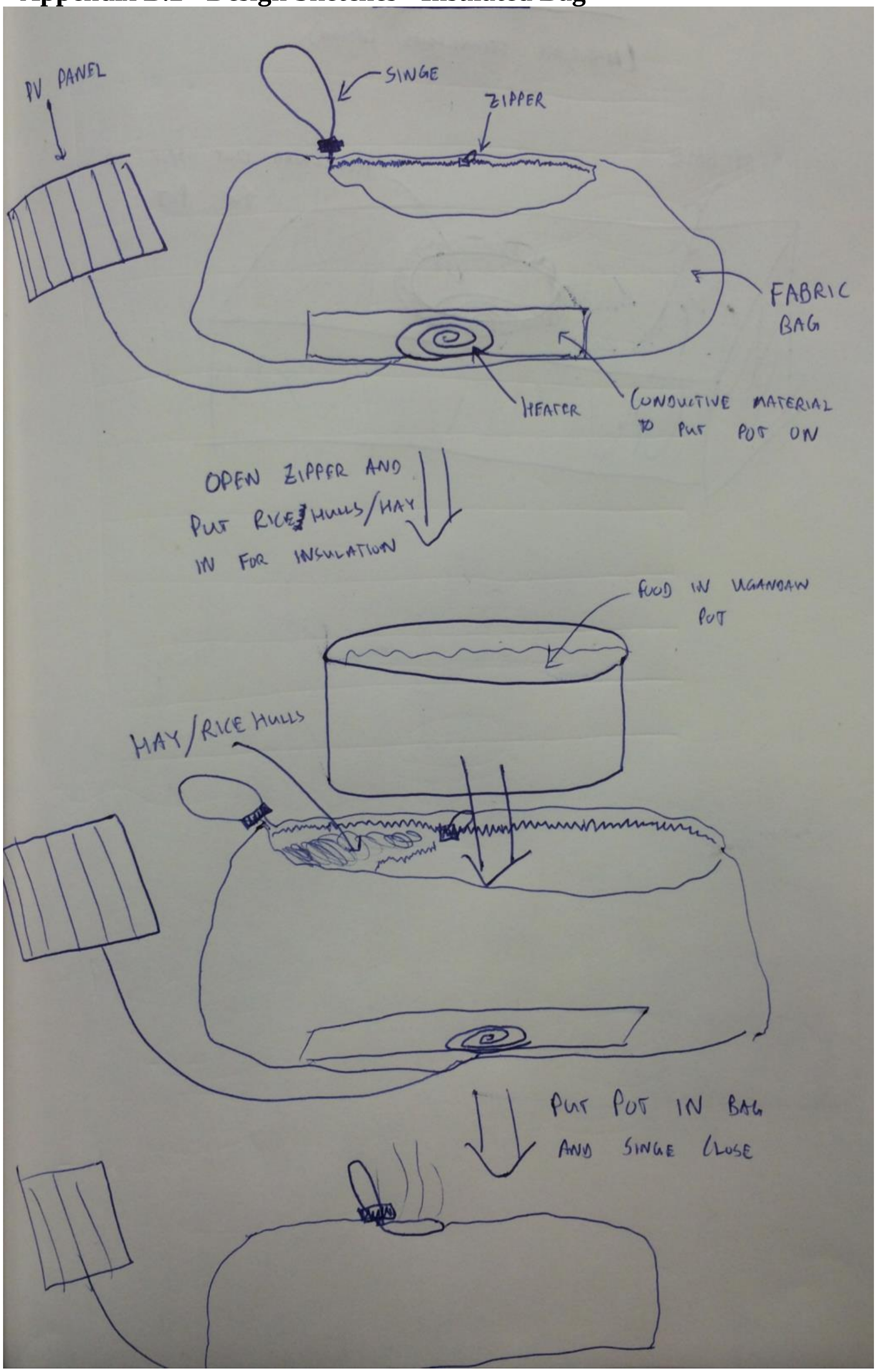
Template Revision: 0.9 Date: [illegible]
Christopher Battles

# Appendix B Design Sketches

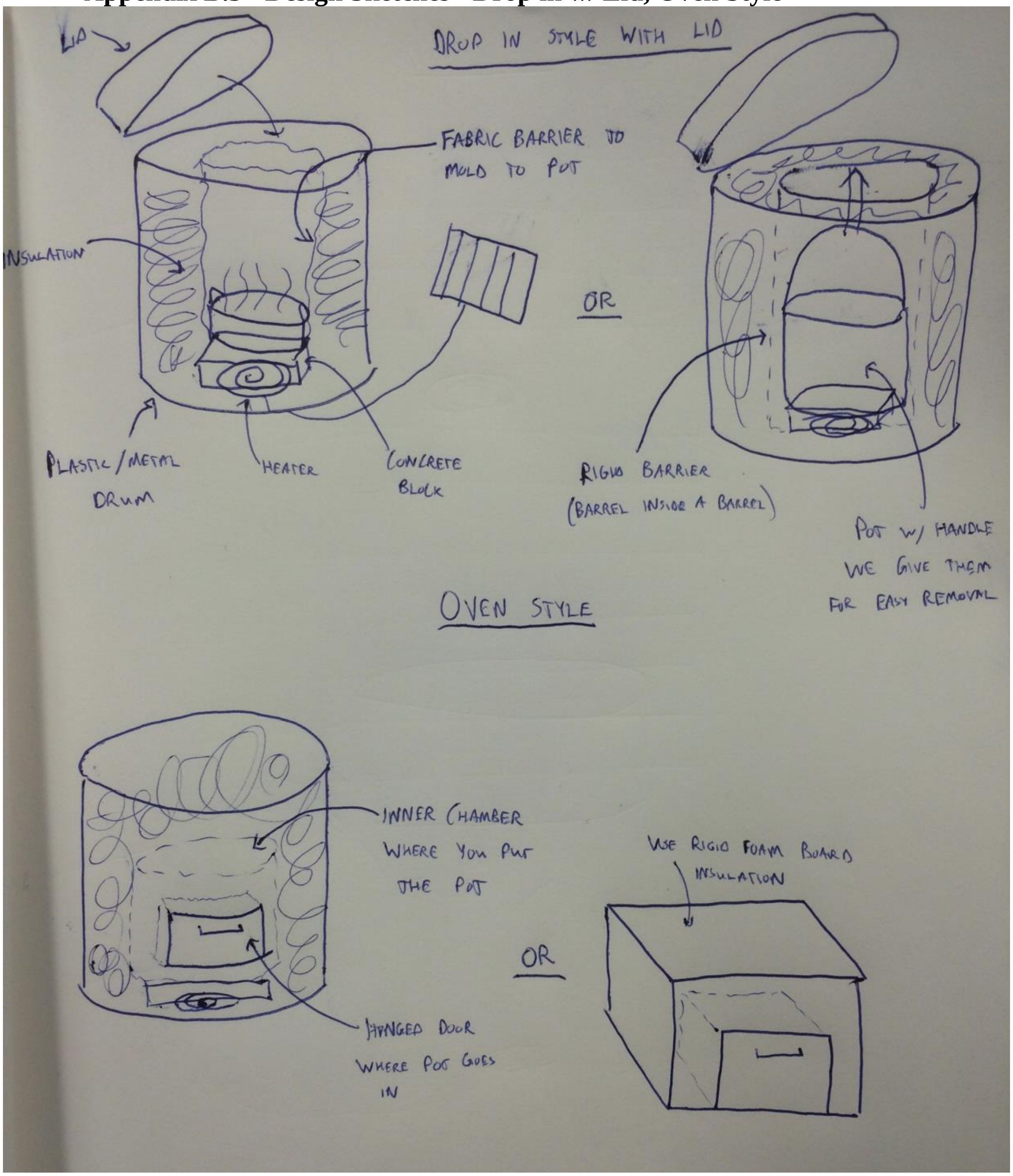
## Appendix B.1- Design Sketches - Hay Bale Design



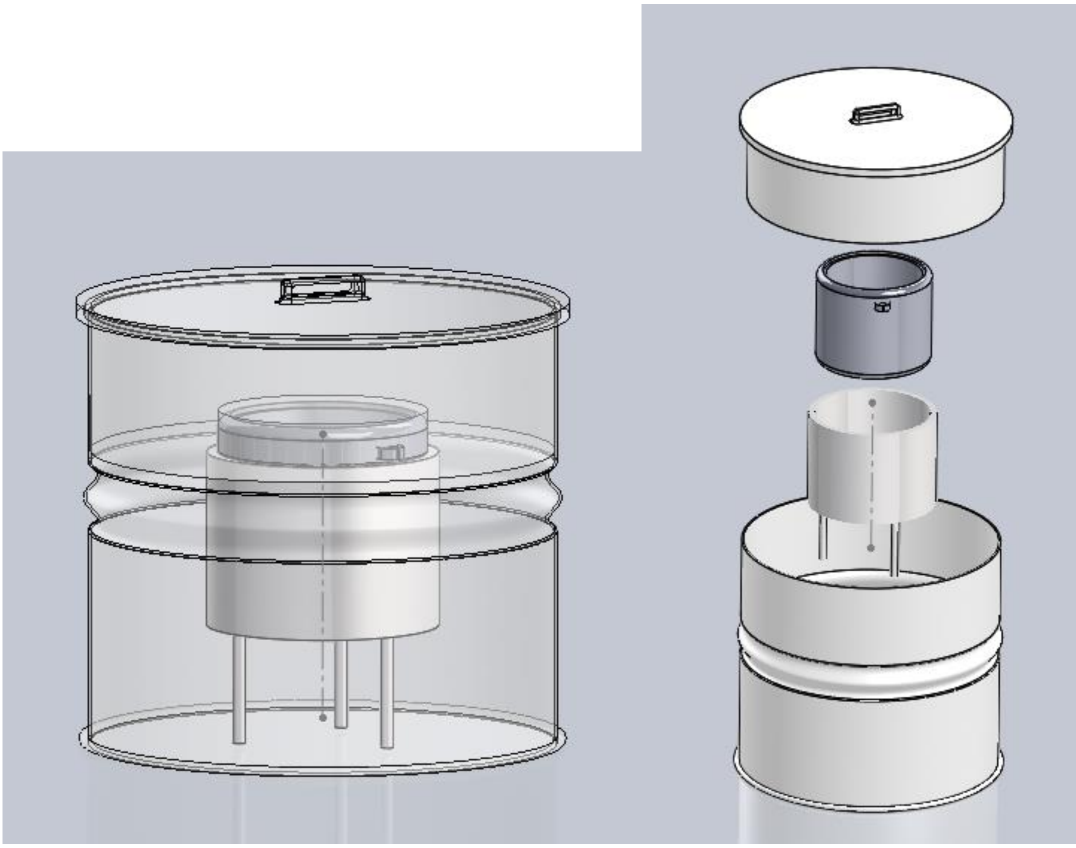
**Appendix B.2 - Design Sketches - Insulated Bag**



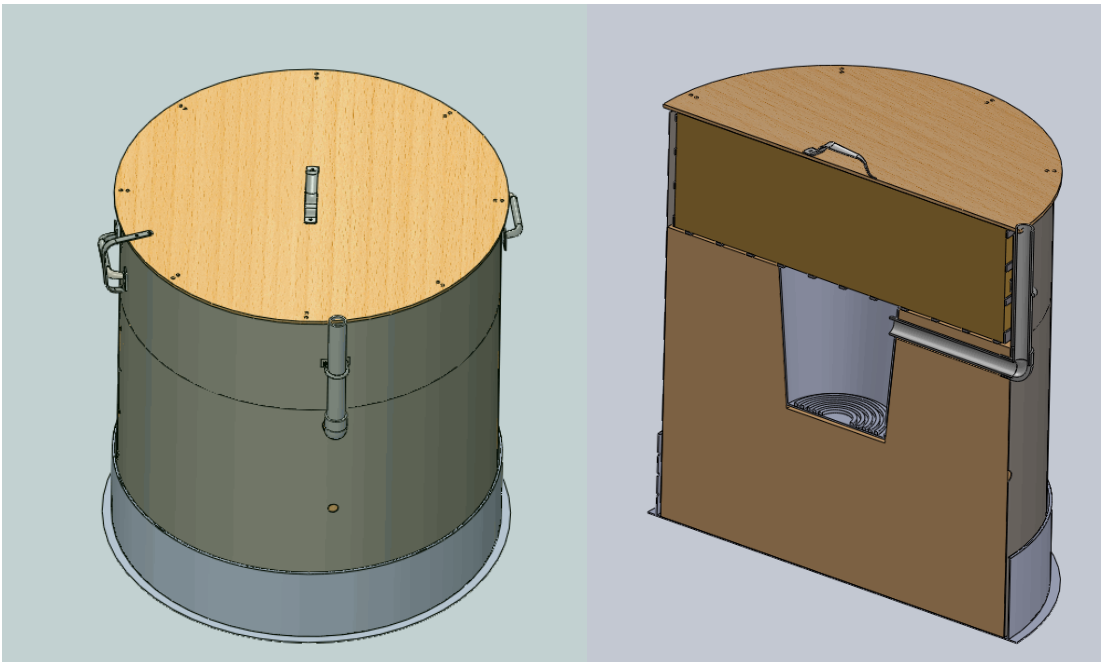
**Appendix B.3 - Design Sketches - Drop in w/ Lid, Oven Style**



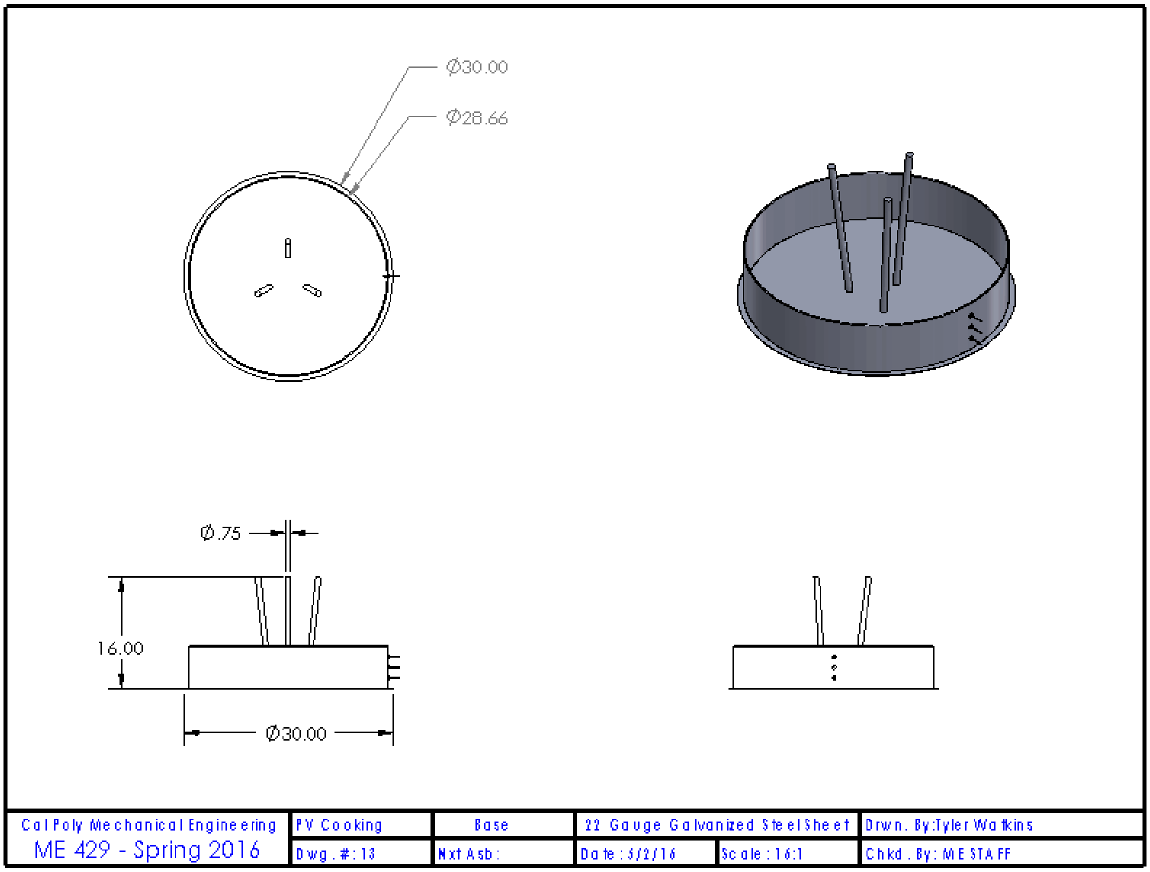
**Appendix B.4 - Design Decision - Barrel with lid Design**



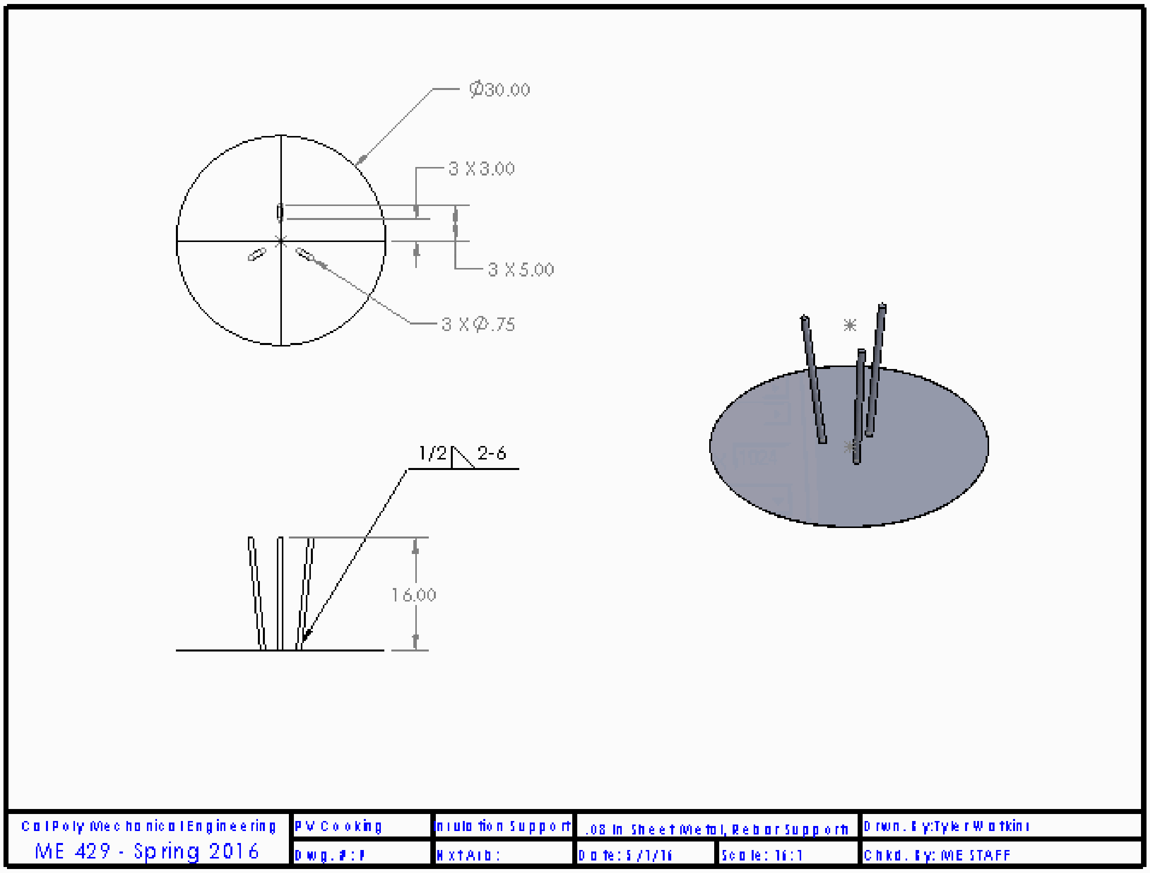
**Appendix C: Final design CAD**



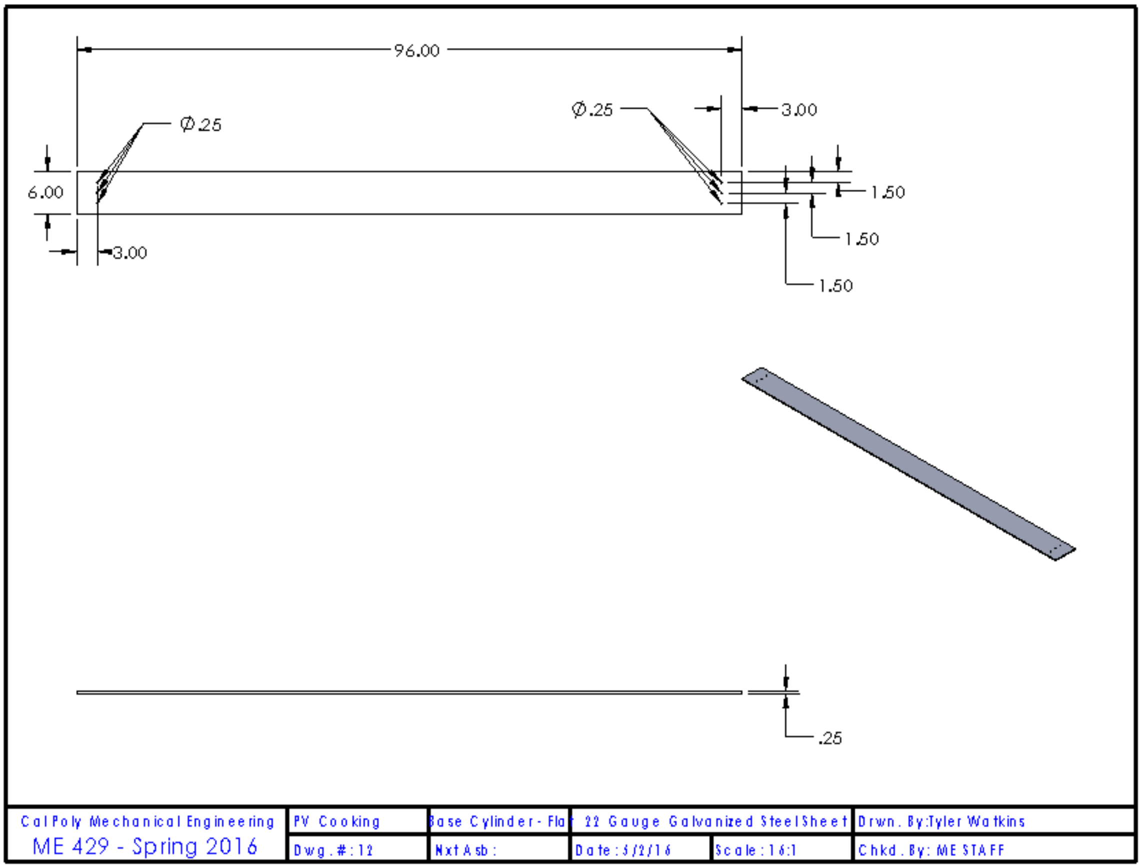
## C.1 - Base Assembly



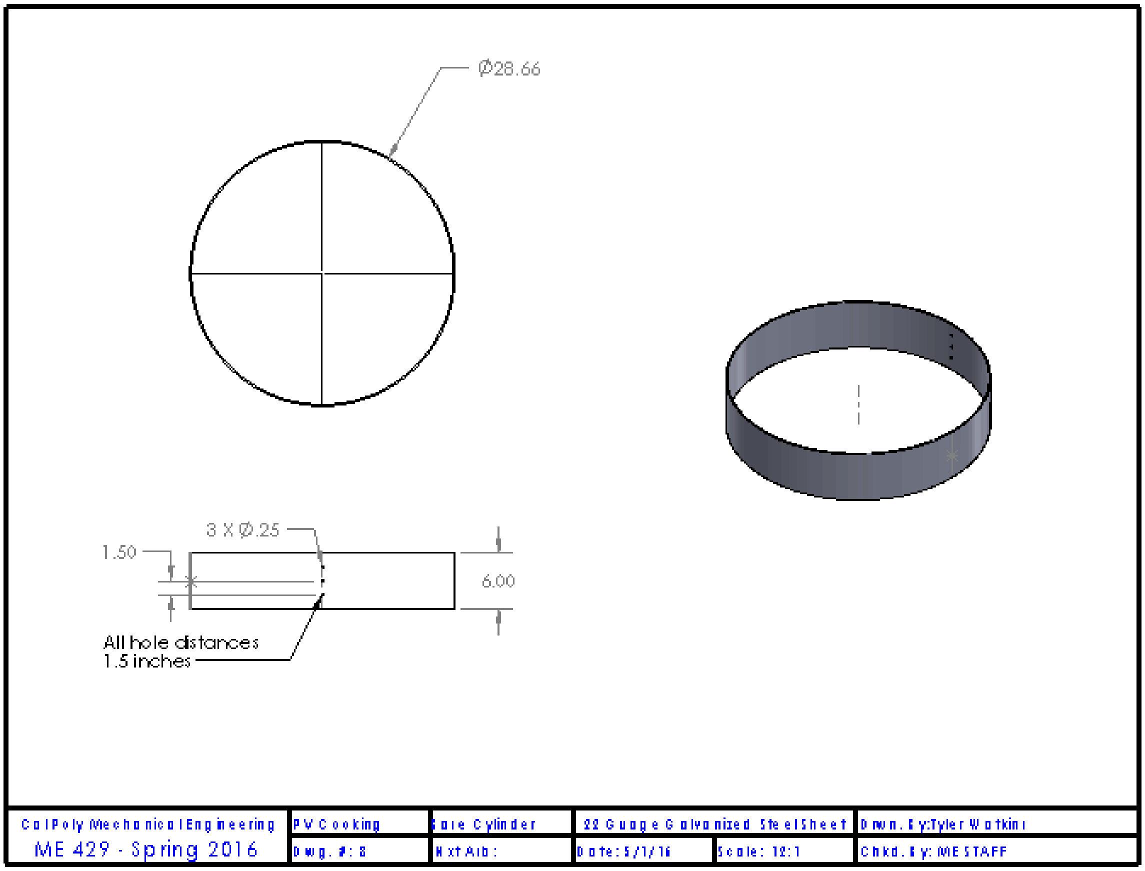
### C.1.1 - Base Plate



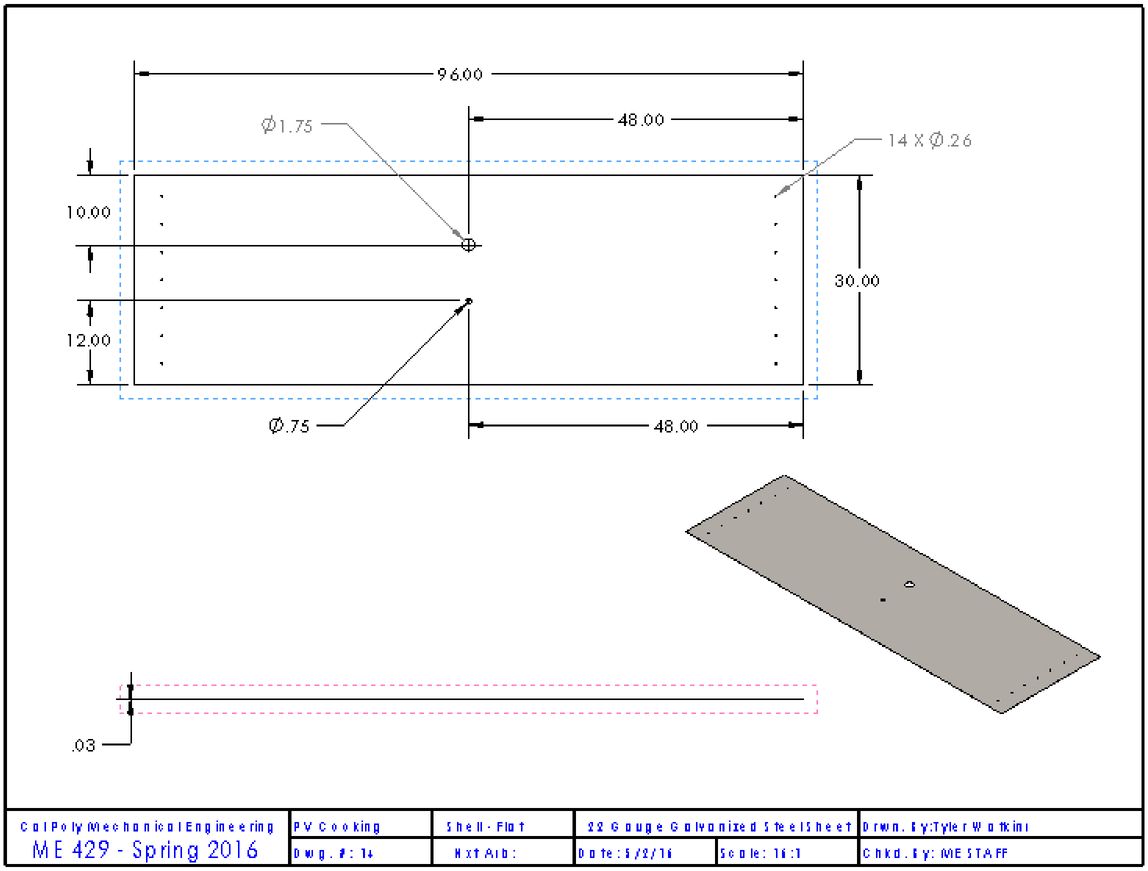
## C.1.2 - Base Cylinder - flat



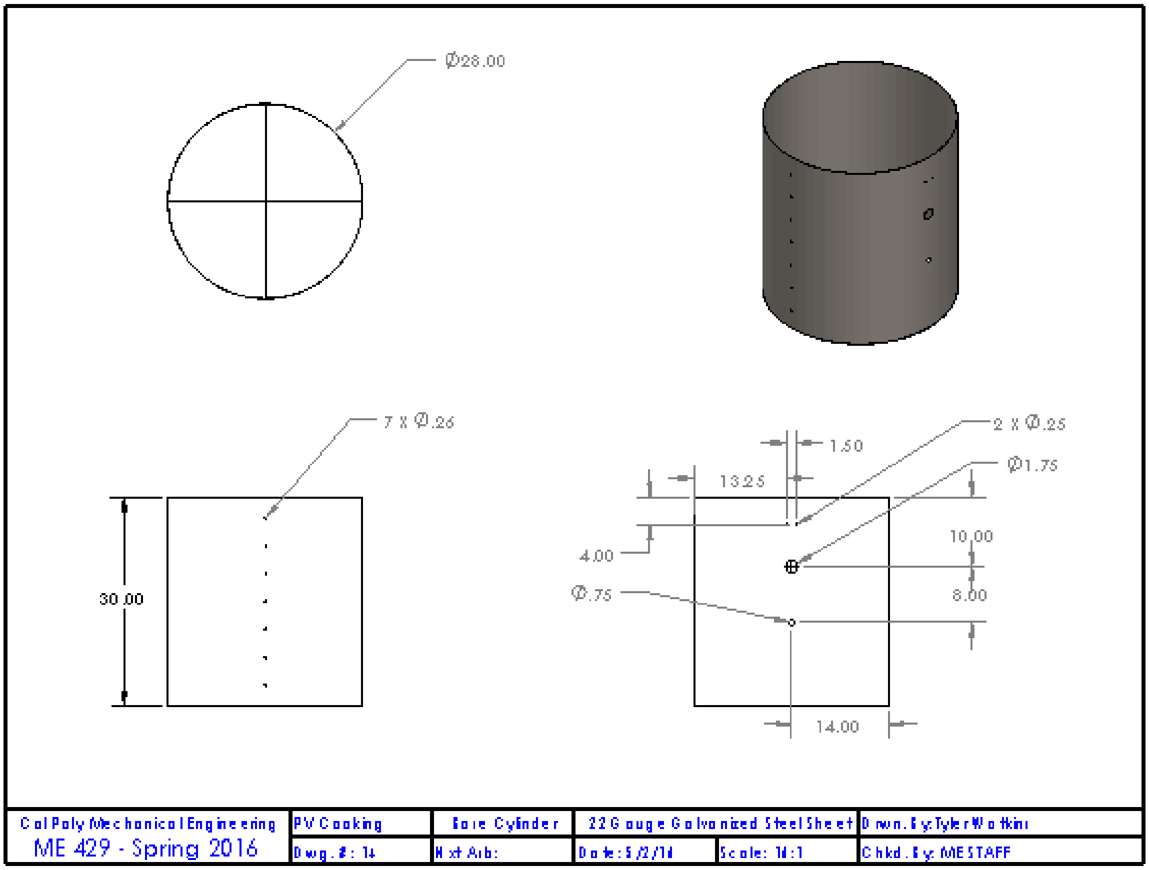
**C.1.3 - Base Cylinder - Rolled**



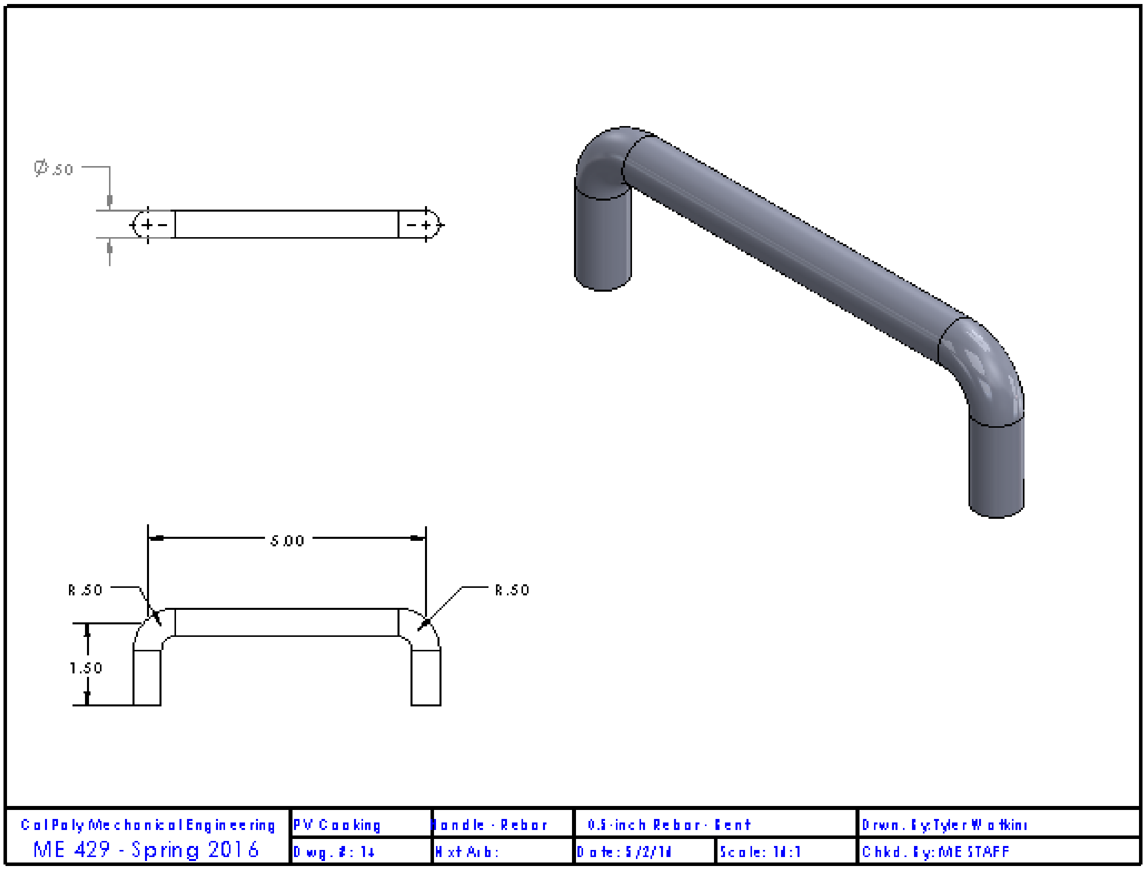
**C.2.1 - Shell - Flat**



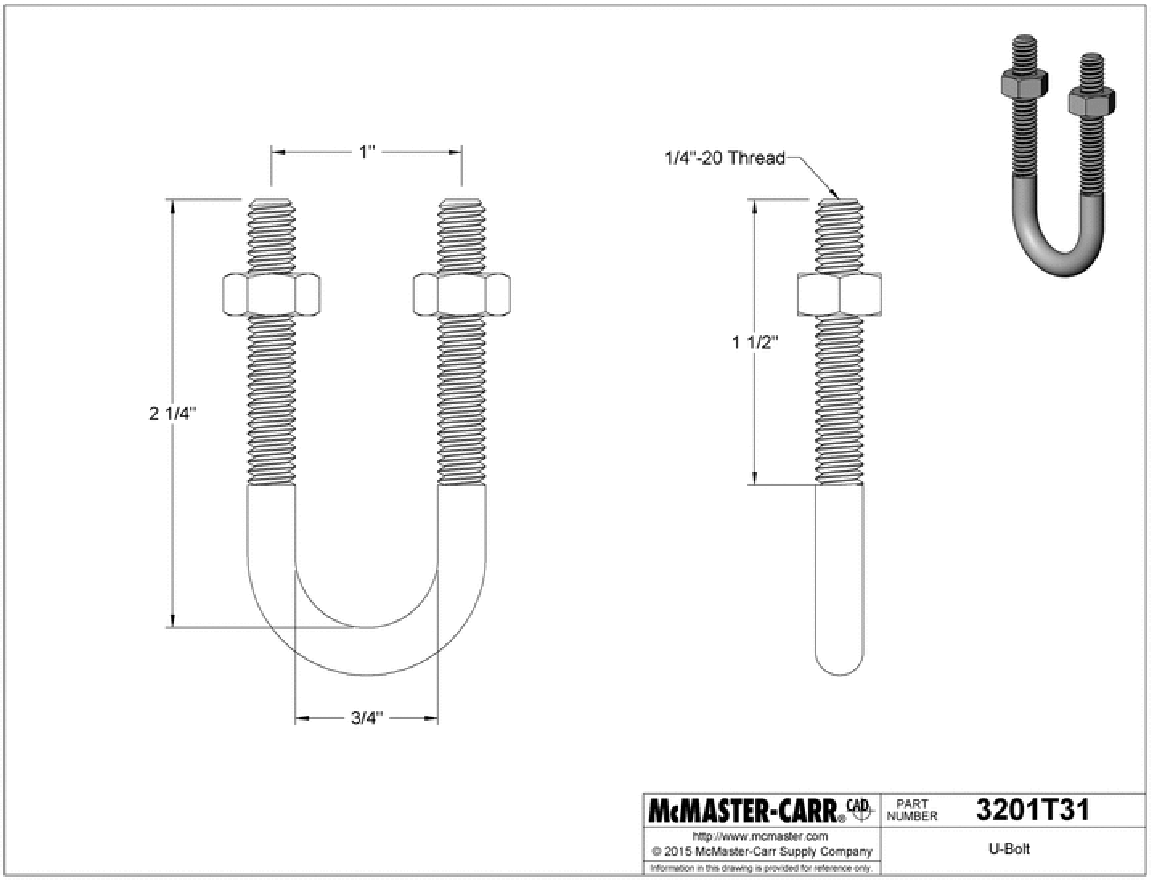
**C.2.2 - Shell - Rolled**



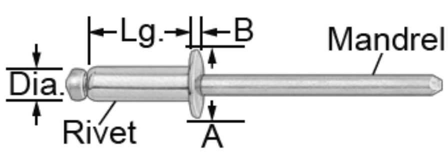
## C.2.3 - Rebar Handles - Bent

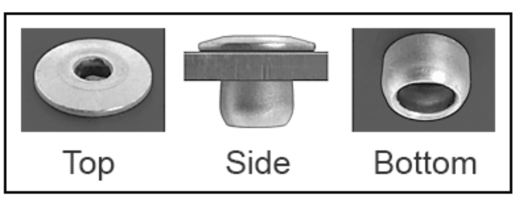


### C.2.4 - U-Bolt




### C.2.5 - ¼-inch Rivet

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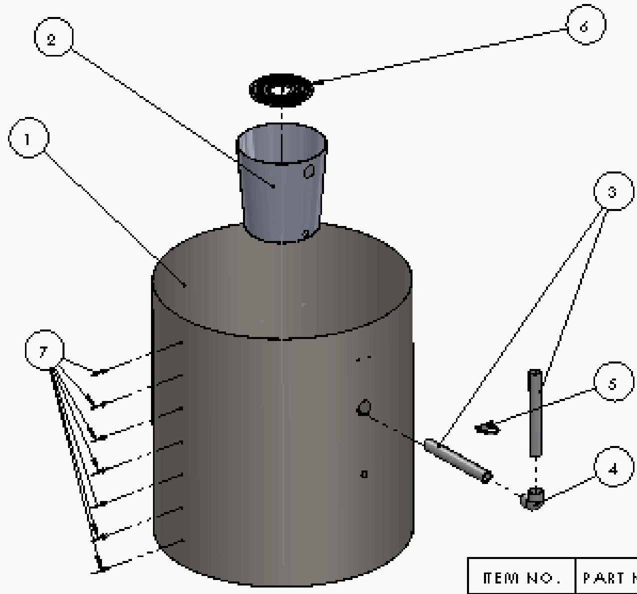
$4.96 per pack of 10
97525A550

| | |
|---|---|
| Material Thickness Range | 0.063"-0.25" |
| Length | 0.5" |
| Head Diameter (A) | 0.525" |
| Head Height (B) | 0.08" |
| Shear Strength | 1,700 lbs. |
| Tensile Strength | 2,100 lbs. |
| Additional Specifications | Domed—18-8 Stainless Steel<br>1/4" Dia.—For Hole Size: 0.257"-0.261" (Drill Size F) |
| RoHS | Compliant |

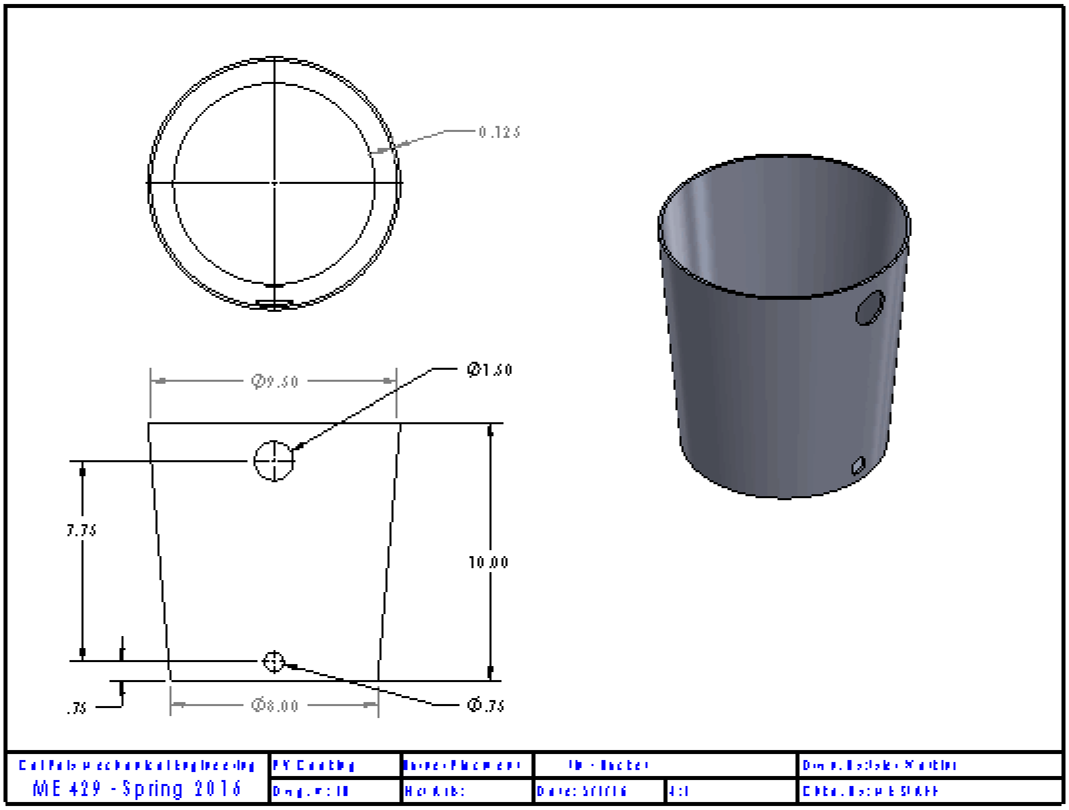
**C.2.6 - Outer Cylinder Sub-Assembly**



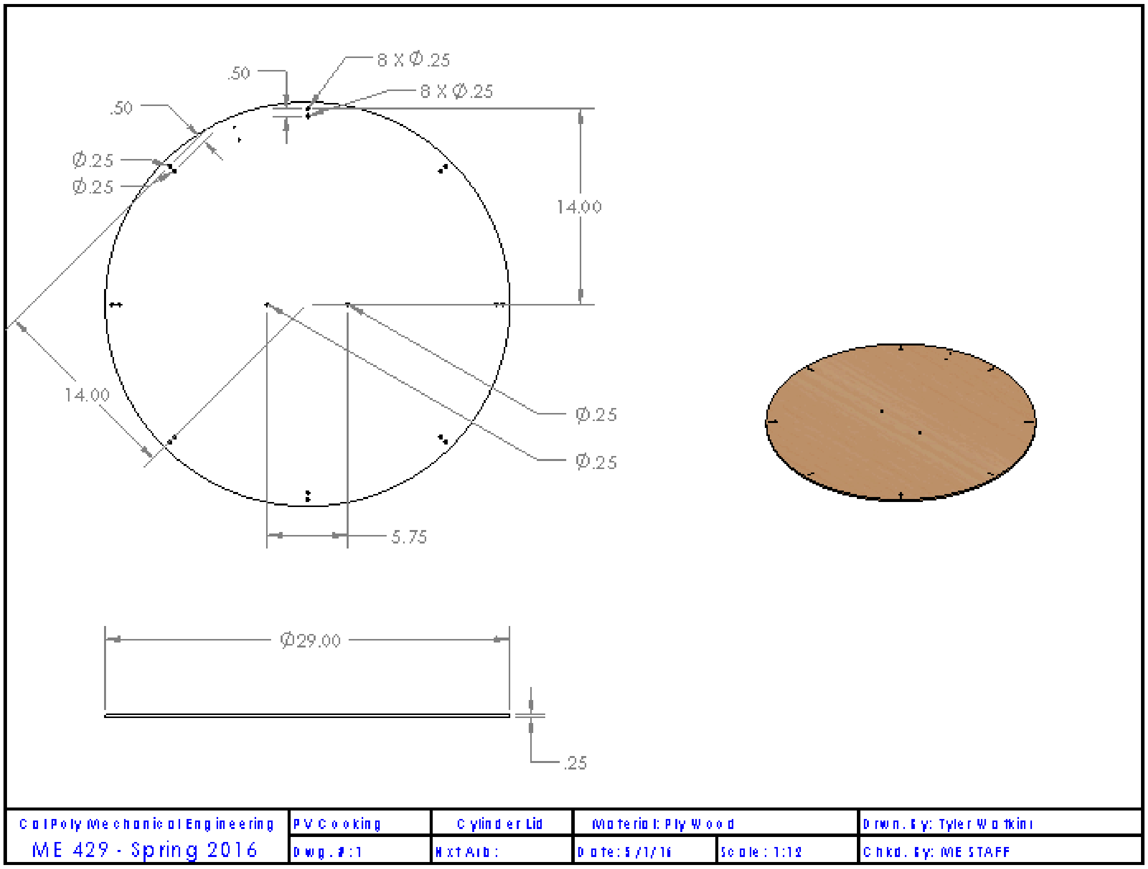

| ITEM NO. | PART NUMBER | DESCRIPTION | Middle/QTY. |
|---|---|---|---|
| 1 | shell | Sheet Metal shell | 1 |
| 2 | bucket | Burner support | 1 |
| 3 | 48925K93 | PVC Ventilation | 2 |
| 4 | 4880K23 | PVC Elbow | 1 |
| 5 | 2936T71 | U-Bolt | 1 |
| 6 | Burner | Heating Element | 1 |
| 7 | rivet | For Shell Structure | 7 |

| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering<br>ME 429 - Spring 2016 | PV Cooking | Inulation Support | .25in Chicken Wire | | Drwn. By:Tyler Watkins |
| | Dwg. #: 2 | Nxt Asb: | Date: 5/1/16 | Scale: 32:1 | Chkd. By: ME STAFF |

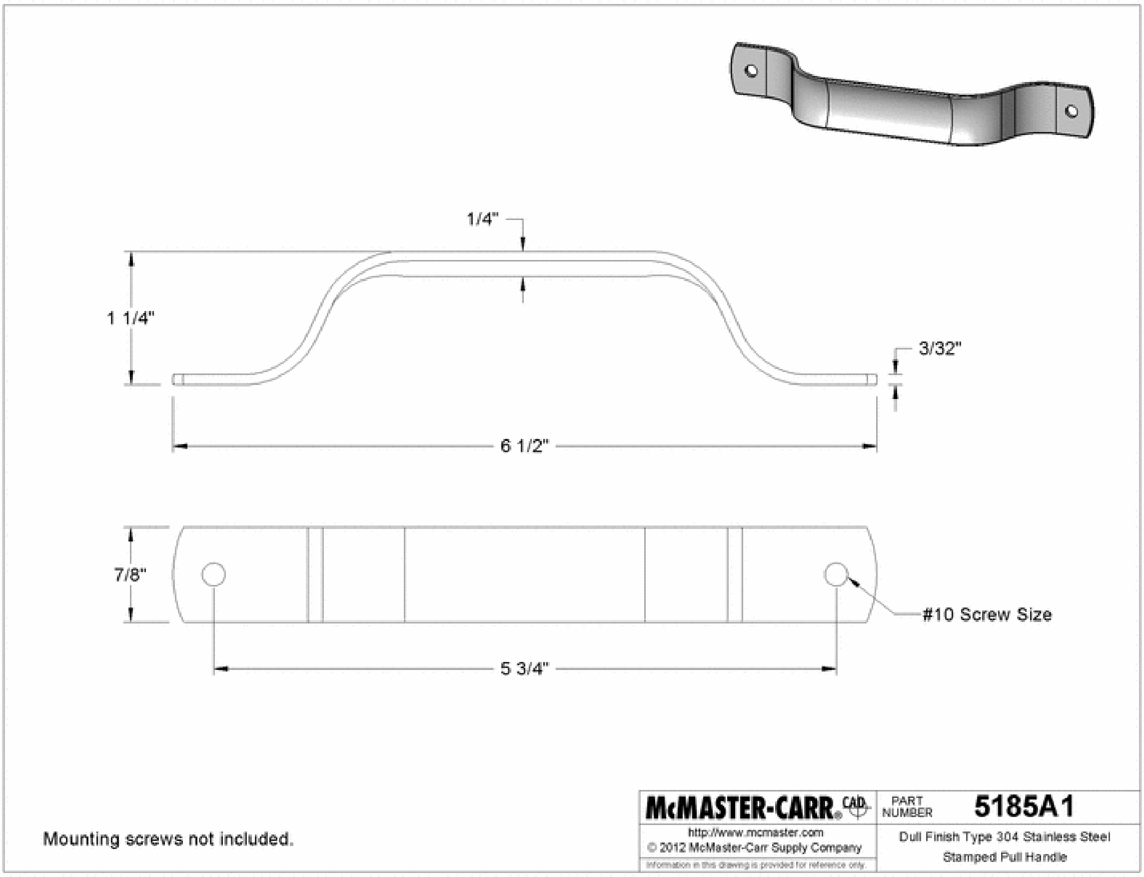
**C.3.1 - Cooking Chamber Structure**



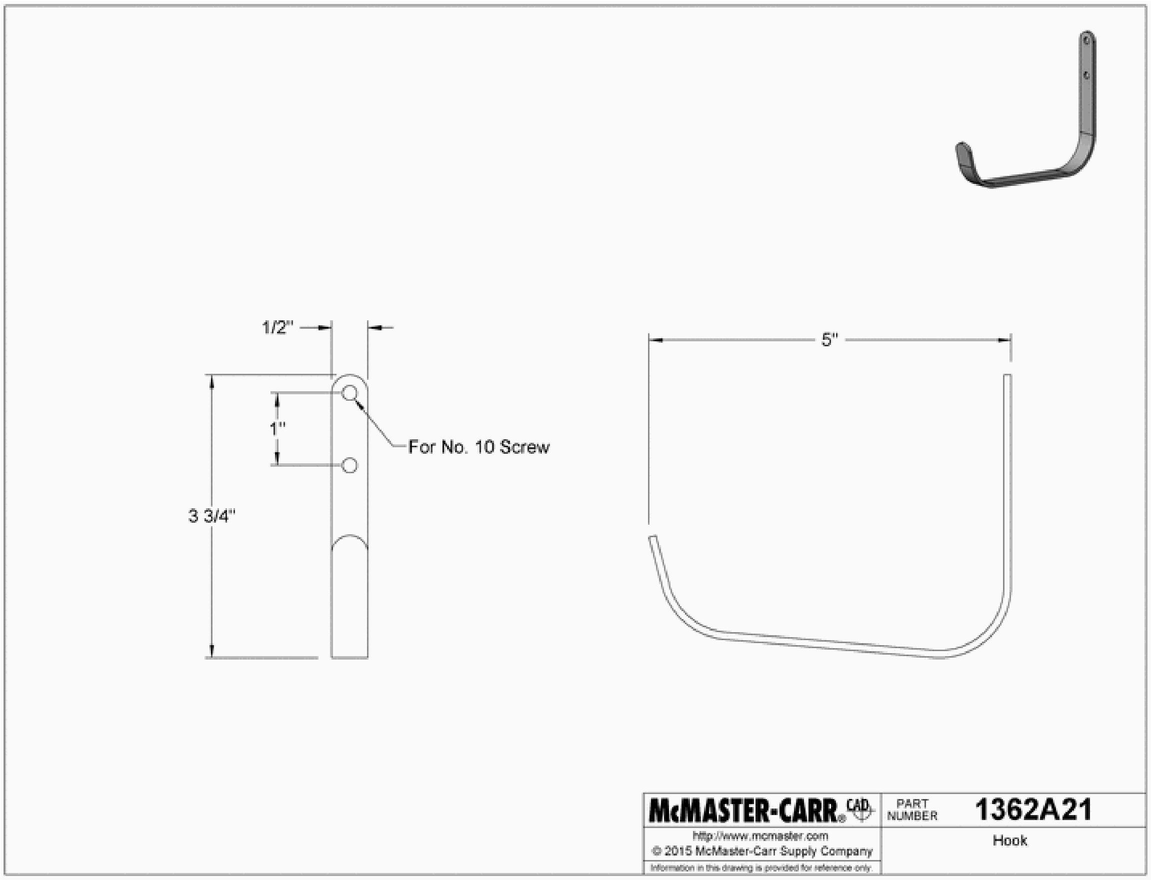
### C.4.1 - Lid


8 X Ø.25
8 X Ø.25
.50
.50
Ø.25
Ø.25
14.00
14.00
Ø.25
Ø.25
5.75
Ø29.00
.25
CalPoly Mechanical Engineering
ME 429 - Spring 2016
PV Cooking
Dwg.#:1
Cylinder Lid
Nxt Asb:
Material: Ply Wood
Date: 5/1/16
Scale: 1:12
Drwn. By: Tyler Watkins
Chkd. By: ME STAFF

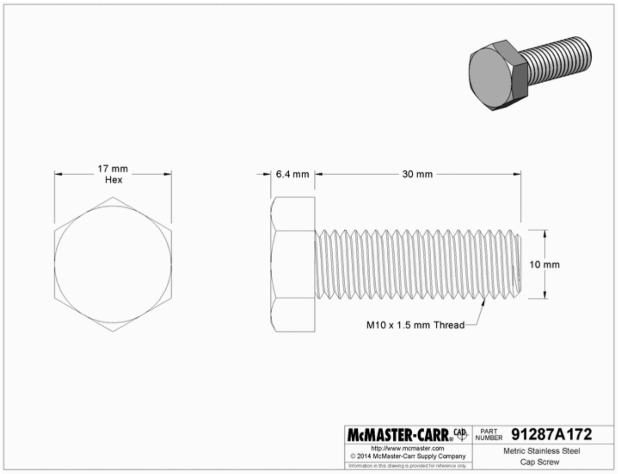
**C.4.2 - Handle**


1/4"
1 1/4"
3/32"
6 1/2"
7/8"
#10 Screw Size
5 3/4"
Mounting screws not included.
McMASTER-CARR
PART NUMBER
5185A1
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Dull Finish Type 304 Stainless Steel
Stamped Pull Handle

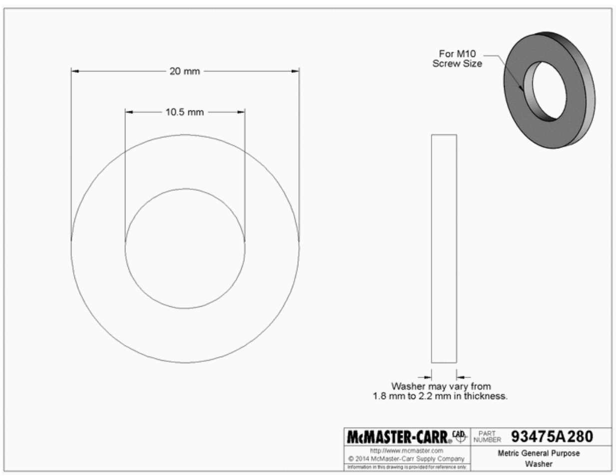
**C.4.3 - Hook**


1/2"
1"
For No. 10 Screw
3 3/4"
5"
McMASTER-CARR
PART NUMBER
1362A21
http://www.mcmaster.com
© 2015 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Hook

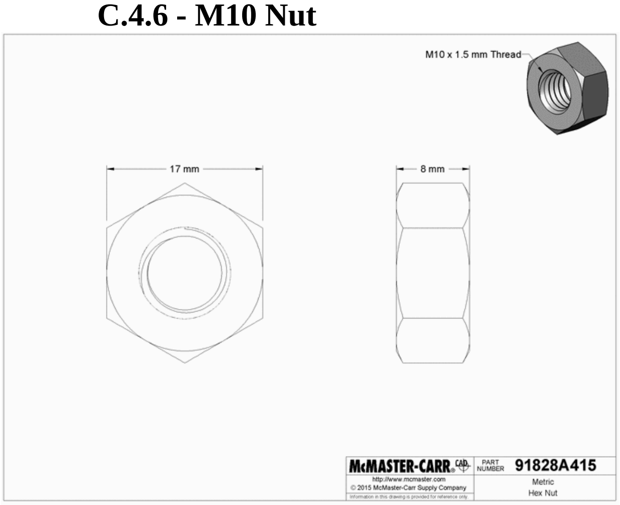
### C.4.4 - M10 bolt



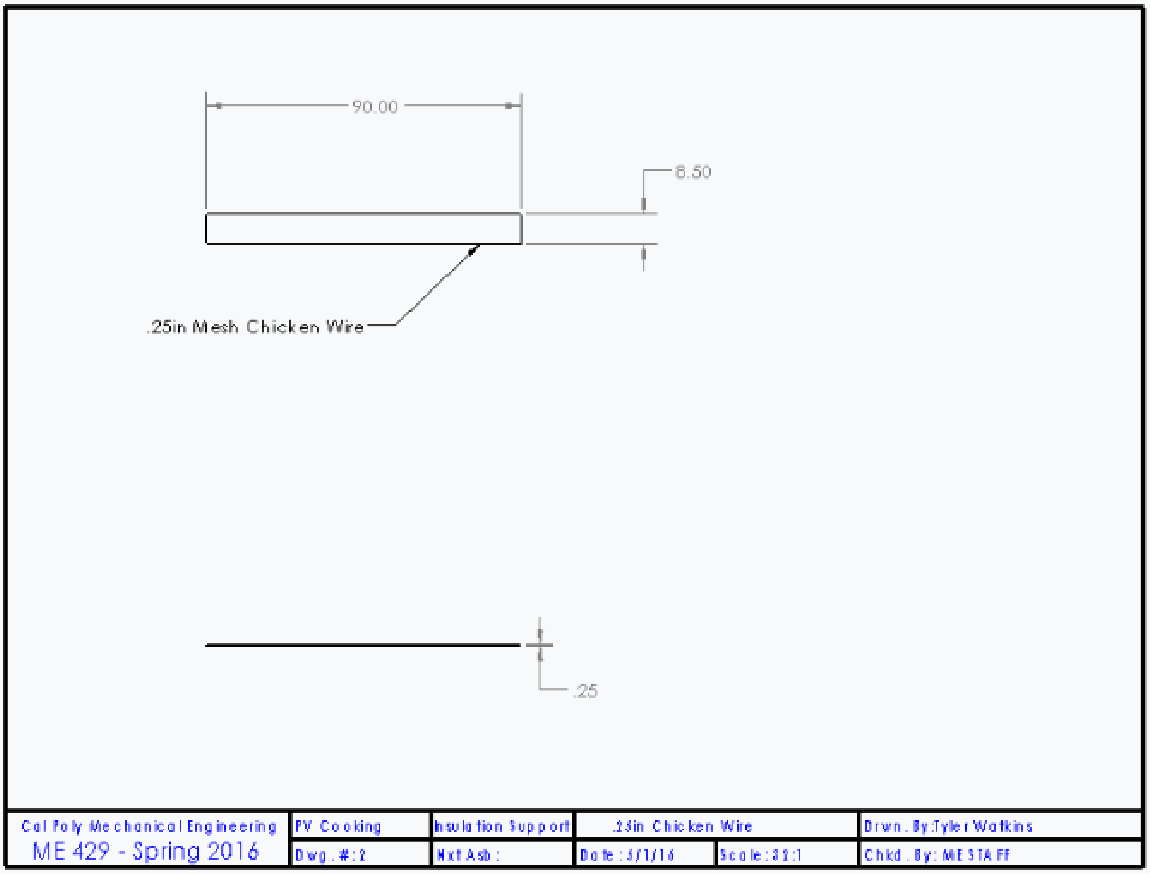

### C.4.5 - M10 Washer



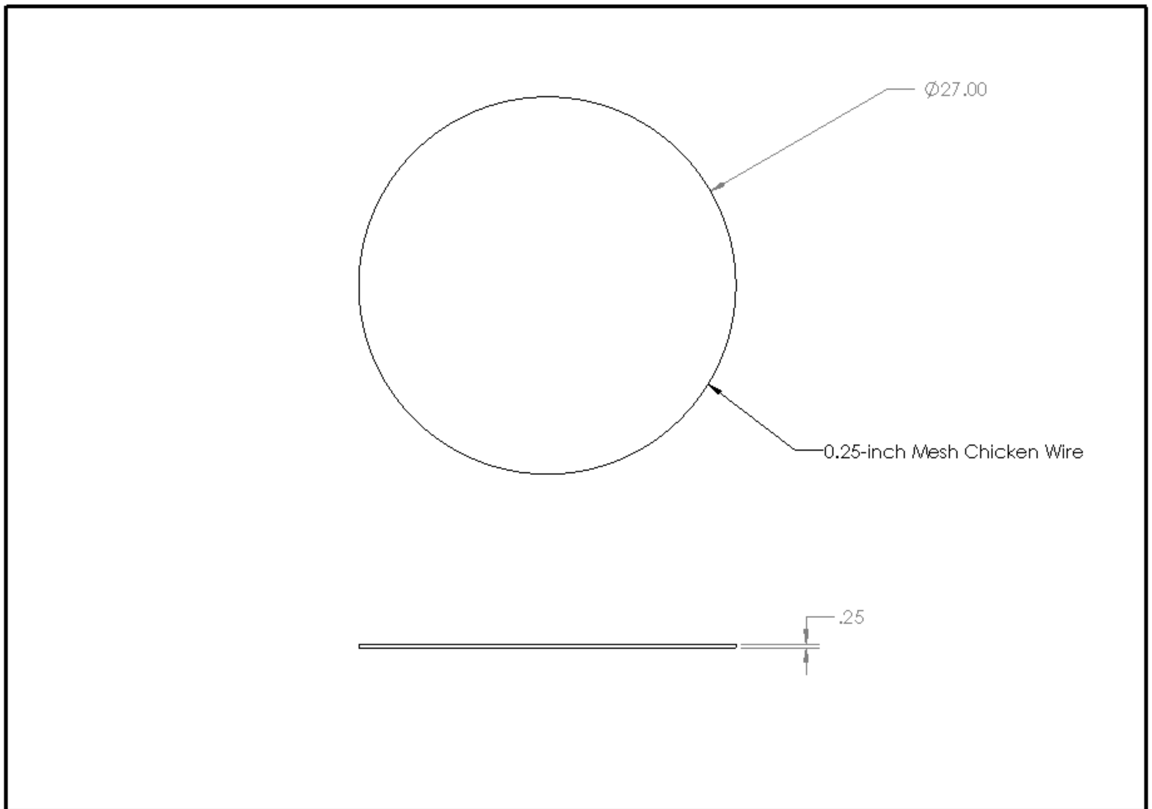

### C.4.6 - M10 Nut



**C.4.7 - Chicken Wire - Flat**

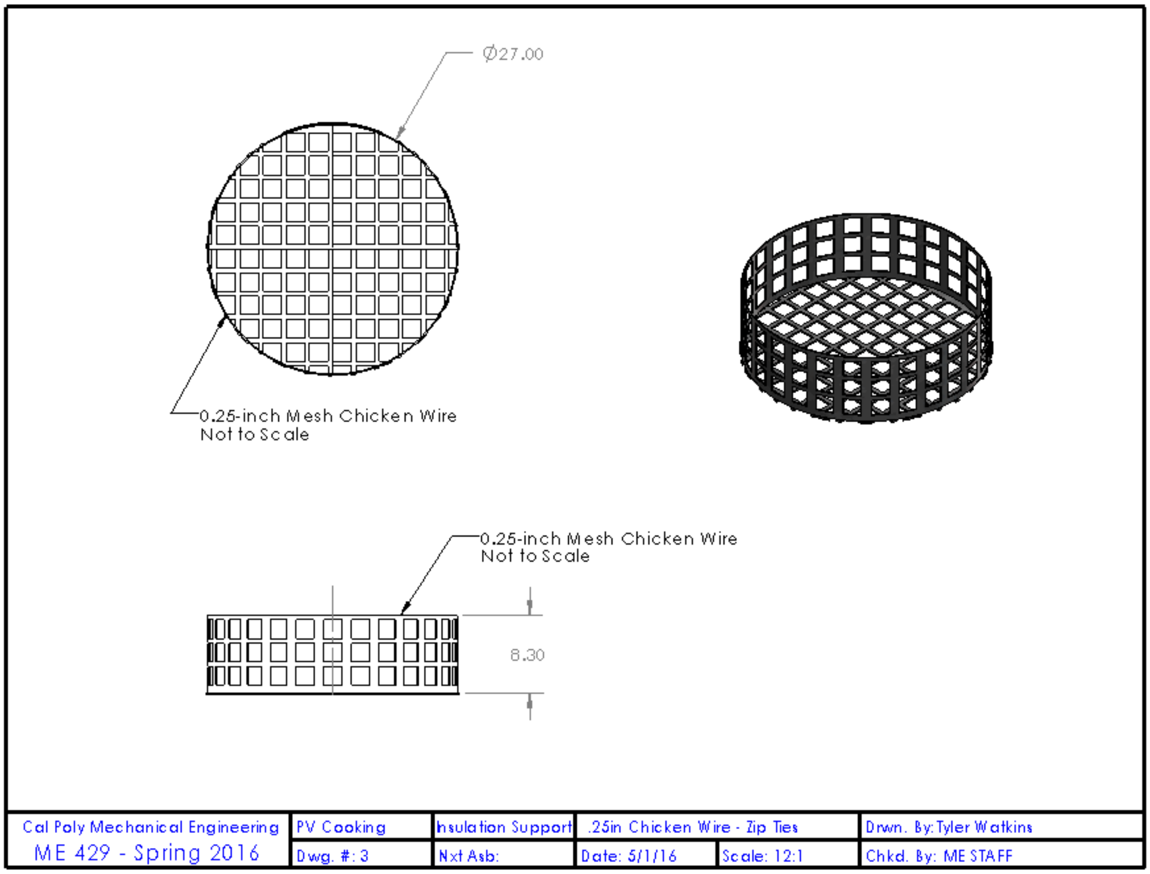


**C.4.8 - Chicken Wire - Base**

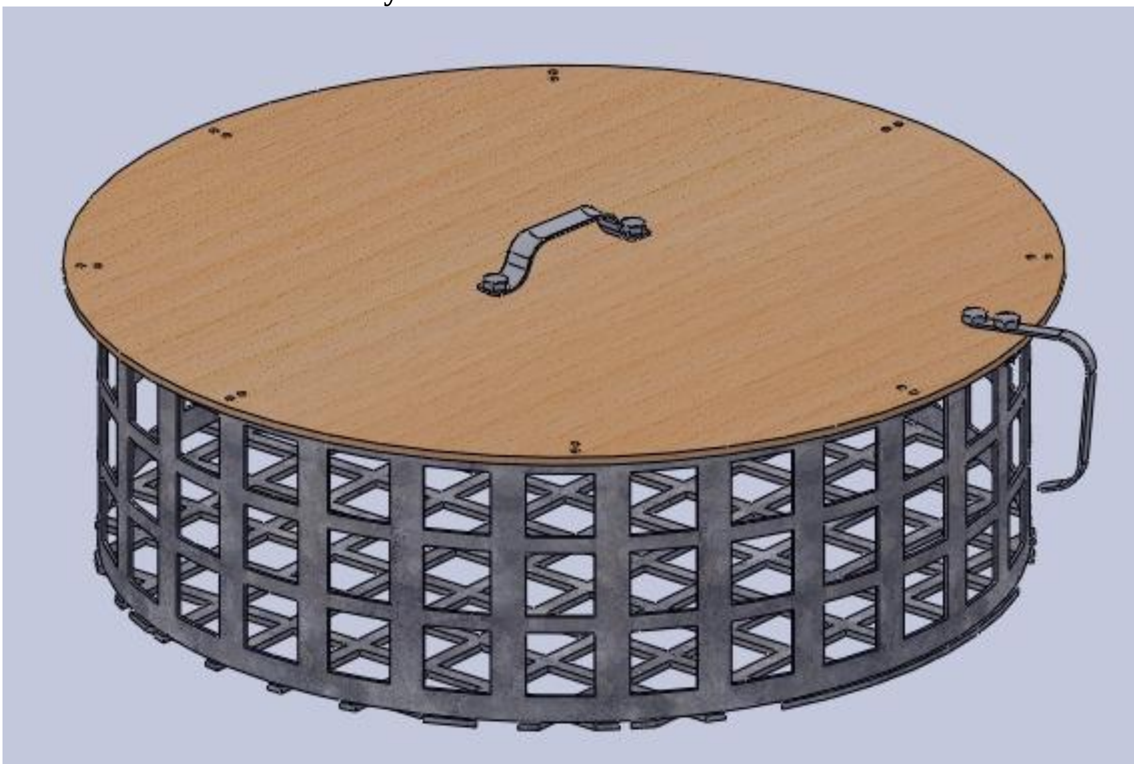



| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering | PV Cooking | Insulation Support | .25in Chicken Wire | | Drwn. By: Tyler Watkins |
| ME 429 - Spring 2016 | Dwg. #: 3 | Nxt Asb: | Date: 5/1/16 | Scale: 8:1 | Chkd. By: ME STAFF |

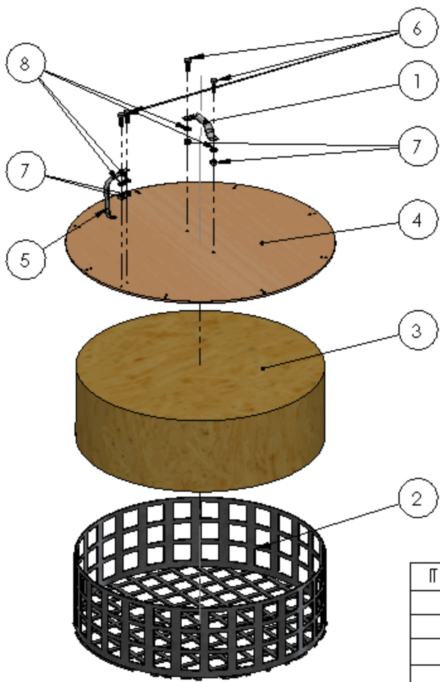
**C.4.9 - Chicken Wire Assembled**



**C.4.10 - Lid Assembly**



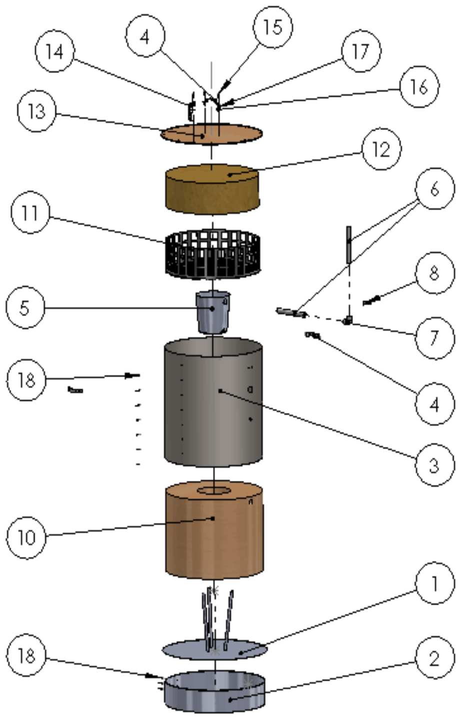
## C.4.11 - Lid Exploded Assembly




| ITEM NO. | PART NUMBER | DESCRIPTION | Top/QTY. |
|---|---|---|---|
| 1 | 5185A1 | Handle | 1 |
| 2 | Chicken wire | 0.25 Mesh | 1 |
| 3 | Top_Insulation | Straw Insulation | 1 |
| 4 | lid | Top to Solar Cooker | 1 |
| 5 | 1362A210 | Hook | 1 |
| 6 | 91287A172 | Bolt | 4 |
| 7 | 91828A415 | Nut | 4 |
| 8 | 93475A280 | Washer | 4 |

| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering | PV Cooking | Assemby | Top Section Assembly - Exploded | | Drwn. By:Tyler Watkins |
| ME 429 - Spring 2016 | Dwg. #: 18 | Nxt Asb: | Date: 5/1/16 | Scale: 12:1 | Chkd. By: ME STAFF |

## C.5 - Full Assembly - Exploded View




| ITEM NO. | Part | Default/ QTY. |
|---|---|---|
| 1 | baseNEW | 1 |
| 2 | base2NEW | 1 |
| 3 | shell | 1 |
| 4 | 5185A1 | 3 |
| 5 | bucket | 1 |
| 6 | 48925K93 - PVC Pipe | 2 |
| 7 | 4880K23 - PVC Elbow | 1 |
| 8 | 2936T71- U-Bolt | 1 |
| 9 | Burner | 1 |
| 10 | insulation_bottom | 1 |
| 11 | Chicken wire | 1 |
| 12 | Top_Insulation | 1 |
| 13 | lid | 1 |
| 14 | 1362A210 - Hook | 1 |
| 15 | 91287A172 - Bolt | 4 |
| 16 | 91828A415 - Nut | 4 |
| 17 | 93475A280 - Washer | 4 |
| 18 | rivet | 10 |

| | | | | | |
|---|---|---|---|---|---|
| Cal Poly Mechanical Engineering ME 429 - Spring 2016 | PV Cooking | Full Assembly | Multiple | | Drwn. By:Tyler Watkins |
| | Dwg. #: 20 | Nxt Asb: | Date: 5/1/16 | Scale: 32:1 | Chkd. By: ME STAFF |

## Appendix D: List of Vendors, Contact information and pricing

Prototype materials:

- **Home Depot - homedepot.com**
    - 32 gal. Garbage can $14.97
    - Chicken wire $10.99
    - 18qt tin can $9.88
    - Tarp $6.99
    - 16-gauge wire $3.00
    - 8” electric range burner $7.50
- **Eco Worthy Solar - ecoworthysolar.com**
    - 100W solar panel $113.99

# Appendix E: Vendor supplied Component Specifications and Data Sheets

Data sheet not available from supplier. There is only information on the website.

## 100W Solar Panel Specifications:

| Specification | |
|---|---|
| Rated power | 100w |
| Voc | 22.41 |
| Vop | 17.9V |
| Short circuit current (Isc) | 6.2A |
| Working current (Iop) | 5.59A |
| Output Tolerance | ±3% |
| Temperate coefficient of Isc | (010+/- 0.01 )%/ °C |
| Temperate coefficient of Voc | - (0.38 +/-0.01 )%/ °C |
| Temperate coefficient of power Voc | -0.47%/°C |
| Temperature range | -40°Cto +80°C |
| Frame | Heavy duty aluminum |
| Kind of glass and its thickness | Low Iron, high transparency tempered glass of 3.2mm |
| SLA Battery Voltage | 12V |
| Dimensions (L x W x H)mm | 1189*543*35mm (46.8"x21.4"x1.4") |
| Weight | 19.85lbs (9kg) |
| Warranty | 25-year transferable power output warranty: 5-year/95% efficiency rate, 10-year/90% efficiency rate, 25-year/80% efficiency rate<br>5-year material and workmanship warranty |

# Appendix F: Detailed Supporting Analysis

## DFMEA Analysis

| | | | | | | | | | Action Results | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item / Function | Potential Failure Mode | Potential Effect(s) of Failure | Sev | Potential Cause(s) / Mechanism(s) of Failure | Occur | Crit | Recommended Action(s) | Responsibility & Target Completion Date | Actions Taken | Sev | Occur | Crit |
| Low resistance heating element modified to increase power output | heater shorts out | heater stops working | 8 | Poor connections combined with power suddenly switched on | 4 | 32 | Design a burner that does not need to be modified | Omar - done | Solder leads. Protectev from water. Leads away from conductive shell and chamber | 8 | 2 | 16 |
| Low resistance heating element modified to increase power output | wire connections corrode or disconnect | heater stops working | 8 | Poor connections, moving the stove around, water getting on burner | 2 | 16 | Design a burner that does not need to be modified | Omar -Done | Solder leads to burner. Wire connector attachements | 8 | 2 | 16 |
| Low resistance heating element modified to increase power output | wire connections spark | oven catches on fire | 10 | Poor connections combined with power suddenly switched on | 3 | 30 | Design a burner that does not need to be modified | Omar - Done | Insulation contained away from lead connections where spark is possible | 10 | 2 | 20 |
| Removable pot holding food | food spills out when pot gets put in or taken out of oven | food is lost, food spills on electrical system and shorts it out, food spills on insulation | 7 | Method of inserting and removing pot | 4 | 28 | Add in a spill catcher over electrical system, design handle for pot | Chris - 5/13/16 | Electrical systems stored in waterproof container | 7 | 2 | 14 |
| Removable pot holding food | hot pot is exposed to user | user gets burnt | 9 | No safety warning or directions for protecting your hand when removing pot | 3 | 27 | put safety warnings on pot, add handle | Tyler - done | Oven mitts.safety warnings | 9 | 1 | 9 |
| Insulation allows inside chamber to get hot enough to cook food | haye becomes less insulative | oven does not get hot enough or takes longer to cook | 5 | water/food spilling onto insulation, rain getting into oven | 4 | 20 | Cover insulatiion | Chris - done | replaceable insulation. Ventilation | 5 | 3 | 15 |
| Wire coming out of oven connecting to PV | wire frays or gets cut | no power to oven | 8 | Sharp edge of hole cut into inner or outer chamber | 2 | 16 | put rubber grommets in holes to protect wire | Tyler - done | rubber grommet on contact point with outer cylinder | 8 | 1 | 8 |

# Appendix G: Other Information

## Steady State Conductive Heat Transfer Calculations

| Conductive Heat Transfer |
|---|
| Steady State Conditions |

| Variables |
|---|
| A = Area |
| Q = Heat |
| K= Thermal Conductivity |
| A = Area |
| L= Length |
| R= Thermal Resistance |
| r1= inner radius |
| r2 = outer radius |

| | Heat Equations | | |
|---|---|---|---|
| 1-D Heat transfer | 1-D Heat transfer | R - Cylinder | R- Sphere |
| $Q = \frac{KA\,\Delta T}{L}$ | $Q = \frac{\Delta T}{R}$ | $R = \frac{\ln(r_2/r_1)}{2*\pi*H\times K}$ | $R = \frac{(1/r_1)-(1/r_2)}{4*\pi*K}$ |

| Cylinder Anaylsis | | | Model for barrel design | | |
|---|---|---|---|---|---|
| Heat Available (W) | Thermal Conductivity (W/mK) | Temp Change (K) | Cylinder Radius Outer (m) | Cylinder Radius Inner(m) | Height (m) |
| 30 | 0.06 | 75 | 0.279 | 0.14 | 0.5 |
| | Heat Loss (W) | | Thermal Resistance | | |
| | 20.50144269 | | 3.658279133 | | |
| | Max Temp Possible (Celcius) | | | | |
| | 134.748374 | | | | |

| Water Calcs | | | |
|---|---|---|---|
| Q=mcT | | | |
| Q (J/s) | mass (Kg) | C (J/(Kg°C)) | T (°C) |
| 79.49855731 | 1 | 4160 | 75 |
| | Heat needed to Boil | | |
| | 312000 | | |
| | time to boil (s) | | |
| | 3924.599522 | | |
| | **time to boil (min)** | | |
| | **65.40999203** | | |

## Appendix H: Owner's Manual

**Structure**

The first step in creating a solar stove is to create a structure for the insulation. There are several versions of a structure that one can make. The structure should be rigid since it will be holding the insulating material around the pot. We demonstrate 2 designs, one of which is dug into the ground, the other uses reed mats and metal rods. The design of the structure is not constrained to these ideas as any design that fits your materials and situation as holds the insulation will work.

The in ground structure:
The hole-in-ground design consists of digging a hole approximately 3 ft. by 3 ft. and 12 inches deep. The hole should allow for at least enough insulation to fulfill the minimum requirement as defined by figure H-1. In order to elevate the structure from the ground, the dirt and clay mixture that was left over from the hole is used to create mud bricks mixed with straw. The mud to straw ratio is 1:1. A structure using wooden 2x4's is used to maintain the shape of the bricks. Once the bricks have dried, they are laid out and stacked around the hole so that the total height of the cooker is about 2 feet high (height is determined by the insulation requirement - this is merely a suggestion)

**Insulation**

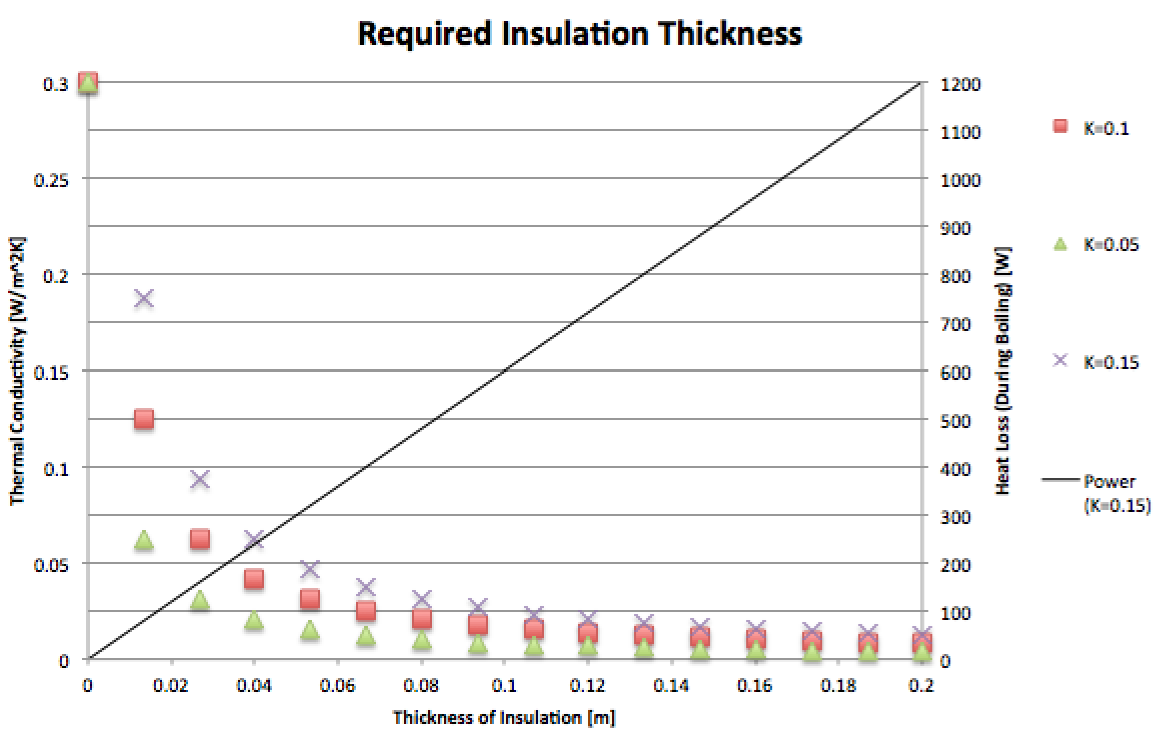



**Figure H-1:** This figure shows the minimum thickness of insulation required based on the thermal conductivity (black line). The three sets of data points represent the heat loss

during boiling with different thicknesses of insulation. Each curve represents a different thermal conductivity: 0.05, 0.1, and 0.15 $W/m^2K$.

While figure H-1 shows the minimum thickness of insulation needed, it is advised to use much more insulation than that in order to limit heat losses and boil at a faster rate. Note that at their respective thermal conductivities, it would be impossible to boil water with any less insulation than the thickness relating to 100 Watts of heat loss. We only have 100 watts available, so if more heat is being lost it will never reach a boiling temperature. As you can see from the shape of the curves, increasing the insulation thickness becomes less effective at greater values as the data asymptotically approaches no heat loss. With that being said, it is still important to use much more than the minimum value as is reasonable economically of your insulation type and structure.

**Heating Element**

The optimum resistance for the heating element is determined by the solar panel characteristics. The figure H-2 below illustrates several solar panel power ratings. This figure can be used to estimate the ideal resistance for your heating element.

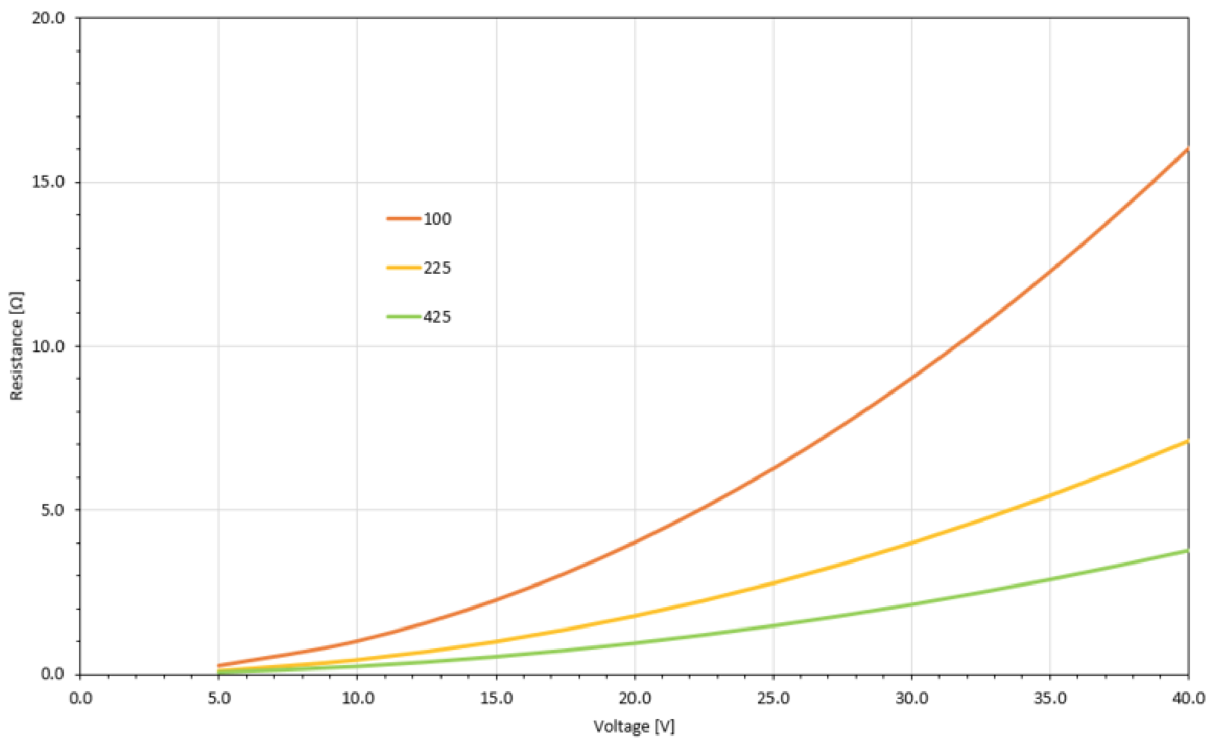



**Figure H-2**: Ideal burner resistance for specific PV power and voltage.

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